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EMERGENCY STOPPING OF AIRCRAFT WHICH OVER-RUN AIRFIELD RUNWAYS

by

J. THOMLINSON

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This Report was presented at the Thirteenth Meeting of the Flight Test Panel, held from 20th to 25th October, 1958, in Copenhagen, Denmark

SUMMARY

This paper discusses in broad principle many of the various ways that have either been tried or proposed for stopping aircraft which over-run an airfield runway. Soft ground over-run area schemes are discussed and not regarded with favour. Mechanical schemes are considered where special fittings, such as an arresting hook, are provided on the aircraft, and also where no such fittings are provided. Aircraft 'catching' devices, such as arresting wires and barrier nets, are examined and the energy absorption systems which might be used are described. Some of the more important points in the mechanics of these schemes are briefly mentioned.

SOMMAIRE

Il s'agit dans cette communication d'un exposé à grands traits de plusieurs des méthodes nombreuses soit déjà essayées soit proposées en vue de l'arrêt des avions qui dépassent les limites d'une piste. Des projets utilisant du sol mou sont examinés mais sont considérés peu avantageux. Sont également traités des projets qui consistent à employer un appareillage mécanique et selon lesquels les avions sont munis de dispositifs spéciaux, tel qu'un crochet d'arrêt, ainsi que des projets qui ne prévoient pas de tels dispositifs. Des dispositifs destinés à accrocher les avions, tels que câbles d'arrêt et barrières de sécurité sont examinés et des systèmes d'absorption d'énergie pouvant être employés sont décrits. Certains des aspects plus importants de la mécanique de ces projets sont sommairement exposés.

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NOTATION

T	rope tension at the aircraft
T_0	value of T on engagement
T_{max}	maximum value of T
M	aircraft mass
P	resistance developed by the arrester gear
E	equivalent mass of the moving parts of the gear
l, x, ϕ	see Figure 28
V	engaging speed
V_{crit}	engaging speed which will produce failure
r	length of rope between the rendering points and the aircraft = $l \sec \phi$
v	impact velocity
k	velocity of sound in the rope
m	line density of the rope

EMERGENCY STOPPING OF AIRCRAFT WHICH OVER-RUN AIRFIELD RUNWAYS

J. Thomlinson*

1. INTRODUCTION

Incidents occur, fortunately only infrequently, but with sufficient frequency that they cannot be ignored, in which an aircraft having traversed the length of a runway arrives at the end with some speed and continues into what is usually known as the over-run or overshoot area. The consequences of such a situation depend to a high degree upon the speed with which the aircraft leaves the runway and also upon the type of aircraft, particularly its wheel loading and the nature of the overshoot area, especially if this area extends beyond the airfield boundary and encroaches on buildings or highways.

Over-running may follow either abortive (or rejected) take-off or a landing, the latter being the more frequent.

The circumstances from which over-running may arise are many and varied, including failure of aircraft wheel brakes and iced runway surfaces, to mention but two of the more obvious causes.

It is not the purpose of this paper to examine the sources of trouble (much less suggest solutions) which result in over-running. It is assumed that over-running is inevitable and it is the purpose of this paper to examine the problem of how to mitigate the situation, short of simply providing yet longer runways.

The author of this paper has not examined the loss statistics in respect of lives and material resulting from over-running aircraft, but anyone who reads the newspapers will be aware that here a problem assuredly exists - and to demand that suitable action be taken seems to be reasonable.

It is difficult to assess how much attention is being given to the problem in the various countries of the world; yet it would appear that in civil aviation very little is being done, whilst in the military field the authorities are beginning to be much more conscious of the problem and action is afoot; the higher cost and greater take-off and landing speeds of military aircraft are presumably responsible for the different attitudes.

It should be made known at an early stage of this paper that there is no known general solution to the problem - hence its challenge. Even lengthening a runway, when this is possible, is not a solution, but only a palliative.

The problem, stated in its simplest form, is that of stopping an aircraft from any speed up to its take-off value (which may be as high as 200 knots) within a reasonable distance, and with as little damage to the aircraft as possible. This having been accomplished, the errant aircraft shall be removed from the line of flight,

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and the runway and its environment be restored to its normal state with the least possible delay, so that succeeding aircraft can land, and if circumstances dictate, the overshoot control be effectively cycled again.

It is for consideration whether or not a solution is sought for all speeds up to the maximum possible (e.g. the take-off speed) or whether it is sufficient to take as the design figure a top speed of some lower value (e.g. 60% or 75% of the take-off speed), leaving the overshoot device to cope as best it may with the rare instances of speeds above this value.

A solution to the problem is always sought in the form of a retarding force to be applied to the aircraft on leaving the runway, and maintaining this force until the aircraft is brought to rest. The required retardation varies directly with the square of the initial speed and the length of space within which it is required to bring the aircraft to rest. Table I gives values of the uniform retardation required for initial speeds of up to 200 knots and run-outs of up to 1,000 ft. This implies that the kinetic energy of the aircraft must be extracted and dissipated - this energy, in a normal landing being extracted as heat energy in the wheel brakes and dissipated by natural cooling.

Features to cope with the over-run conditions are not normally designed into an aircraft, and therefore it is a vital part of the present problem to devise ways and means of applying the necessary retarding force to the airframe as usually designed, without regard to the over-run case. However, it might be possible to design small additional fittings to facilitate the application of retardation forces. The one exception to this is a naval carrier-borne aircraft, which is designed at the outset with an arresting hook that is available for use in over-running if an arresting gear is provided.

2. APPLICATION TO THE AIRCRAFT OF RETARDATION FORCES

The backward retarding force, or vector sum of a number of backward forces, should

(a) either be in the vertical plane of symmetry or intersect this plane behind the aircraft centre of gravity, and

(b) lie in an approximately horizontal plane which passes approximately through the aircraft centre of gravity.

The first of these requirements is to ensure that the aircraft is directionally stable during its arrest, it being assumed that steering is not practicable. However, slight directional instability is permissible, in which case the aircraft will continuously deviate from its original path. This is permissible within limits but should not be allowed to develop to the extent of ground looping.

The second requirement implies that the arresting forces shall not apply excessive pitching movements - either nose-up or nose-down; but if the retardation is small then some relaxation of this requirement is permissible.

The problem will, in the main, be discussed around the conventional nose-wheeled aircraft having two main wheel units behind the centre of gravity and on either side of the vertical plane of symmetry. The discussion will also apply, in the main, to jet-propelled aircraft. It will be fairly obvious however when the discussion is applicable or not to the various other combinations of aircraft configurations, such as propellered aircraft, tail-wheel undercarriages, bicycle undercarriages, etc.

The points at which arresting forces can be applied to a conventional airframe are

(i) the wheel axles, particularly the main wheels, this force being the reaction to rolling resistance developed between the tyres and the ground - the surface of the ground being specially prepared to develop rolling resistance,

(ii) the main wheel undercarriage struts and associated structure,

(iii) the leading edge of the main plane,

(iv) the leading edge of the tailplane,

(v) the leading edge of the fin,

or (vi) at specially designed fittings, such as an arresting hook as used in naval carrier-borne aircraft, or hooks attached to the main undercarriage struts, or some other such development.

3. APPROACHES TO THE GENERAL PROBLEM

An examination of the list of points at which the arresting forces can be applied suggests two broad approaches to the problem:-

(a) Soft ground over-run areas. Here the ground offers considerable resistance to rolling wheels, even if the brakes are inoperative, the resistance being transmitted to the wheel axles and thence to the whole aircraft structure.

(b) Arresting gear schemes. Here the aircraft on entering the over-run area engages a net or rope, or some such catching device, which in turn is connected to an energy-absorbing mechanism.

Division (b) - and from it could appear to come the most promising overshoot control devices - can (for the purpose of discussion) be divided into two parts:-

(i) Catching devices.

(ii) Energy-absorbing mechanisms.

These items (i) and (ii) can, in general, be discussed quite separately, since usually any catching device can be linked to any energy-absorbing mechanism.

4. SOFT GROUND OVER-RUN AREAS

It is desirable that the resistance offered to the ground by a moving aircraft should be proportional to the weight of the aircraft, but independent of its geometry (particularly the wheel arrangement), so that the retardation (expressed in 'g' units) is the same for all aircraft. Unfortunately this ideal is far from being realized in practice.

The soft ground principle does not conform to the requirement (b) of Section 2, that the arresting force shall be in a horizontal plane close to the c.g. of the aircraft and therefore, unless the ground resistance is of a small order, there is a danger of overloading the nose-wheel, since the nose-wheel will be subjected to both drag loads (from the soft ground) and to down loads (over and above normal static loading), by virtue of the nose-down pitching moment generated by the ground drag loads. This moment will of course increase as the ratio (height of c.g.)/(wheel base) increases.

The action which takes place as an aircraft traverses soft ground is that the kinetic energy of the aircraft is expended in cutting ruts in the ground if the latter is of a plastic and cohesive nature, or the wheels may sink into the ground and proceed to push the earth aside - analogous to viscous fluid drag - particularly if the ground is loose or friable. The action is most probably a combination of each, depending on the speed of the aircraft.

In discussing over-run control it is often suggested that the over-run area be ploughed up - as for agricultural purposes - and this suggestion is sometimes supported by instances where the scheme has worked - as well it may. In some circumstances, virgin ground is effective in a similar way; for example, if a heavy aircraft with high pressure tyres accidentally swings off a concrete runway on to the adjacent verges, the wheels may well cut ruts in the ground and experience considerable resistance, a resistance not always appreciated until efforts are made to haul the aircraft back on to the runway.

First thoughts indicate that a solution to the over-run problem might well be found in the natural ground in the overshoot area. However, the resistance offered to a rolling aircraft by such ground is so variable and, recognizing the strength limitations of an aircraft in respect of such forces, the scheme loses its attractiveness. The variations arise from the variable characteristics of the ground. This may vary from light, loose, sandy material to well compacted, heavy, cohesive soils with good bearing capacity. Variations will occur with different moisture contents and will thus vary with the weather and season of the year. If the ground is ploughed, then the bearing and rolling resistance will vary with the depth of ploughing and this again will vary with the passage of time and the natural consolidation which will occur, and with the growth of vegetation which may develop.

With all these factors in mind it is concluded that one would have very little control over the resistance to be developed, and it is difficult to justify a serious approach to a solution along these lines. Nevertheless this does not exclude the use of such a scheme in particular circumstances and is obviously better than no precautionary measures at all. The author knows of no planned and organised trials of such schemes.

Having abandoned the proposal to use natural ground, either processed (i.e. ploughed) or in its virgin state, attention is turned to schemes where a specially prepared soft surface is used with prospects of achieving greater control of resistance to a moving aircraft. Along these lines several ideas spring to mind. First, it is proposed that on a hard bearing surface such as concrete, is laid a layer of loose material such as sand, gravel or shingle, of a size and depth yet to be determined. The rigid base would control the depth to which the wheels would sink; on natural ground this feature is uncontrollable and is likely to contribute to a high degree to the lack of control of resistance. The wheels of the aircraft as they are forced horizontally through such a bed would experience a resistance which it is considered would vary as some function of the speed of the aircraft and the cross-sectional area of the rut formed in the bed.

Thus, if approximately uniform resistance is required then the depth of the bed would have to increase progressively, and it would have to be matched to the tyre width and to the weight of the aircraft. It follows therefore, that a given bed of gravel would react differently with aircraft of different weights and wheel tyre sizes and is in consequence not of general application. Whilst it is considered that best results would be obtained with pebbles of a uniform size, say about one inch, there are a number of disadvantages. They would not react favourably on high pressure tyres and some would inevitably be thrown-up and damage the aircraft - possibly getting into engine intakes. However, such damage would have to be assessed against the damage resulting from an uncontrolled over-run.

The author knows of three instances where gravel beds have been spread, but at the time of writing have not been engaged by aircraft. Such a bed, unless carefully maintained, will accumulate dust and vegetation would develop, and hence consolidation would result, and an aircraft would ride over rather than through it. Also, in conditions of snow and frost the bed would loose its fluid-like properties, assume solidarity and so be ineffective - ineffective when its use is likely to be in greatest demand.

Another idea, following the same principle but assuming a different practical form, is to provide a lagoon of water, of progressively increasing depth. Resistance here would be due almost entirely to fluid drag, and water being only half the density of gravel would thus demand a much greater depth than for gravel. In addition to its ineffectiveness during periods of hard frost, the initial cost and maintenance make this scheme unattractive. It is of interest to note however that trials of such a scheme were made in Sweden some years ago, but the idea does not appear to have been developed.

With the object of overcoming the ineffectiveness of the previous schemes in conditions of frost, further schemes are proposed of a more sophisticated nature. Here, a rigid base is surfaced with a layer of a foam or sponge rubber sealed in such a way as to exclude moisture, or surfaced with a pneumatic mattress. By virtue of the area to be covered these schemes would be expensive and their rate of deterioration, whether they were engaged by aircraft or not, would be high.

Confidence in, or enthusiasm for, such schemes has not been sufficiently high to lead to trials, within the knowledge of the author.

In closing this review of soft ground over-run areas it should be pointed out that they present a source of danger to undershooting aircraft, since none of them can be unrigged and removed when aircraft are required to approach over them when landing. The possibility of an aircraft undershooting, in its approach for landing, is almost as great as that of overshooting, and therefore this aspect of the problem cannot be ignored.

5. AIRCRAFT ARRESTING GEARS

5.1 General

For the purpose of discussion, the arresting gear problem can be divided into two parts:-

(a) Means for catching hold of the aircraft so that retarding forces may be applied to the aircraft.

(b) Means for absorbing, and then dissipating the kinetic energy of the aircraft.

Whilst it is usual to assume that all the kinetic energy of the aircraft is taken up by the absorber unit, some is dissipated through rolling resistance and aerodynamic drag.

In general, any of the catching devices can be used in conjunction with any of the energy-absorbing devices.

When operating aircraft from naval carriers, arresting gears are an essential part in the operation of landing-on the deck of a carrier. Such aircraft are designed with an arresting hook, which is arranged to engage a steel rope stretched across its flight path and supported a few inches off the deck - the steel rope being an integral part of the energy absorbing system. In an emergency, which may be due to failure of the arresting hook to function correctly, the aircraft is flown into a net which is attached to an energy-absorbing mechanism. These two systems have been in general use for the past 25 years and there is considerable experience in this field which may be applied, modified as necessary, to the problem, of controlling overshooting aircraft on airfields. 'Modified as necessary' is emphasized, because on a carrier the space available is considerably less than is normally available on an airfield.

Thus, whilst stopping distances on a carrier are about 200 to 250 ft, the corresponding distances for an airfield may approach 800 or even 1000 ft. Hence the retardation and the arresting forces are much less on the airfield and the weight penalty on the aircraft, where specially installed structure is provided, is correspondingly less.

Where the catching device is connected to the energy absorber by means of a rope, the weight of rope required is directly proportional to the kinetic energy of the aircraft, but the length of rope is proportional to the stopping distance. This length of rope presents special problems in some designs.

5.2 Catching Devices

Here there are two divisions - that where the aircraft is not specifically designed to be arrested other than by conventional wheel brakes and, maybe, a tail parachute; and that where arresting is considered in the design and appropriate structure is provided. Thus, in the second case, some weight penalty is incurred and, small though it may be, it is usually looked upon with disfavour by aircraft operators - civil or military.

5.2.1 *Conventional Arresting Hook*

By 'conventional' is meant the type of unit normally designed into naval carrier-borne aircraft - as shown in Figure 1. Such a hook would engage with a wire stretched across its path and supported a few inches clear of the ground. The weight of such an installation is 20-30 lb for each 10,000 lb of aircraft for each 'g' unit of retardation developed during the arrest. No damage will be sustained by the aircraft. The aircraft is directionally stable in both pitch and roll and the sensation experienced by personnel in the aircraft is similar to that produced by hard or violent braking in a motor car - 'hard' or 'violent' depending on the level of retardation developed, which in turn depends mainly upon the design of the energy absorber.

The following values are typical for a practical case:-

Weight of aircraft	30,000 lb
Maximum retardation	1g
Weight of entire hook installation	60 lb
Mean retardation	0.8g
Engaging speed	100 knots
Stopping distance	550 ft.

There are minor differences between carrier and airfield over-run operation. On a carrier, in a high proportion of landings, the hook will engage an arresting wire while the aircraft is in flying attitude and the wheel clear of deck. In over-running on an airfield the aircraft will be rolling along the ground and the wheels will roll over the wire before the hook can engage it. The wire is thus set vibrating in a vertical plane, between the wire supports, and chances of engaging the wire are enhanced or prejudiced according to the configuration of the wire at the instant that the hook reaches it. This situation need not present undue difficulties providing that it is recognised and account taken of it in detail design (see Reference 1).

The arresting hook solution to the over-run problem is most probably the neatest and simplest solution that can be devised. There is no damage whatsoever to the aircraft, and the ground equipment is simple and can be made unobtrusive. Provided that the aircraft wheel brakes are not being applied as the aircraft reaches the end of its forward travel, the strain energy in the rope system at this instant will cause the aircraft to roll backwards a little and the arresting hook thus frees itself from

the wire. If pilot control of the hook is provided, it can be raised and the aircraft taxied away, thus clearing the area quickly and resorting the runway for further landings.

With the arrangement described, the stopping of the aircraft and removal from the runway area can be completed in less time than it takes to describe it, for a weight cost to the aircraft of a small fraction of one per cent of its weight.

5.2.2 *Undercarriage Retardation Using Special Fittings*

If the arresting hook scheme is rejected, then one turns next to strong points already existing on the aircraft. The undercarriage provides such strong points.

Brief trials have been made with a simple arresting wire supported at such a height as to be engaged by the nose wheel strut of an aircraft. In this case, even if the retarding force developed is sufficiently low to be within the drag strength of the wheel installation, then the aircraft is directionally unstable and, immediately following engagement, the aircraft will almost certainly start a ground loop; heavy side-loading of all the wheel units will develop and there is a real danger of main wheel unit collapse.

The main undercarriage is the area where a solution is often sought. The object is to apply the arresting force to the main wheel struts, usually by arranging for the nose-wheel to pass over a conventional arresting wire and then, either throwing up the wire so that it is caught on the wheel struts (this method will be discussed later) or using an arrangement of hooks or scoops which will facilitate the application of the arresting force, developed with the arresting wire, directly to undercarriage struts.

Figure 3 shows the configuration of the rope and undercarriage struts and the way in which the struts are subjected to an inboard component of force as well as a retarding force. The arresting wire must engage both struts - a feature which, in many schemes, cannot be developed to be consistently reliable. It seems unreasonable to assume that an aircraft can withstand arresting forces applied to only one main leg. However, trials have shown that the British Hawker Hunter aircraft can withstand such harsh treatment without collapse - the aircraft swinging into a broadside position with heavy side-loading on the main wheels, particularly the uncaught leg.

Forward facing scoops may be fixed to the undercarriage struts, as shown in Figure 4, and are arranged to engage an arresting wire and deflect it clear of the main wheel (which would otherwise roll over the wire) and up on to the main wheel struts. Unless some scissor feature is introduced into the scoop structure, the toe must be well clear of the ground, in order to accomodate tyre deflection. Thus, unless suitable steps are taken to control the vibrations of the arresting wire following the passage over it of the nose-wheel, there is a possibility of the scoop passing over the wire and failing to engage it - or only engaging one leg.

Such scoops are located outside the profile of the main wheels and as such do not lend themselves to neat and clean retraction; they may well have to be left protruding, thus introducing a penalty in drag as well as in weight.

Another method of applying the forces from a conventional arresting wire to the main undercarriage is to provide trailing hooks to each main leg unit. Figure 5(a) shows an example of a hook trailing directly from the main wheel axle; in such an installation the arresting forces will be applied to the aircraft almost exactly as those applied by normal wheel brakes, and there will be a transfer of loading from the main wheels to the nose-wheel. Figure 5(b) shows an arrangement of hook such that the arresting force is applied high up on the leg, thereby reducing the pitching moment on the aircraft by comparison with the arrangement of Figure 5(a).

These two hook arrangements are more suitable for operation with wheel retraction than the scoops on the forward side of wheels. They do, however, impose a weight penalty and it is for serious consideration whether or not to have a very small extra weight penalty and use a conventional arresting hook on the underside of the rear part of the fuselage - noting that if the retardation is of a modest order this extra weight penalty may not, in fact, be incurred.

With the hook arrangements described the aircraft would suffer no damage whatsoever during arresting; but with the scoops some damage may be done to the strut units at points where the arresting wire makes contact.

5.2.3 *Barrier Nets*

It is often argued that an aircraft should not be penalised by having to carry arresting fittings which, in many instances, will never be used in the course of its lifetime. Much thought has therefore been given to catching an aircraft not provided with any special fittings, and we have two types of solution: first there are net arrangements into which the aircraft runs and is enveloped - the net being coupled to energy absorbing units; and there are schemes whereby a conventional arresting wire is used with various means for throwing it up, after the nose wheel has passed over it, so as to be caught by the main undercarriage struts - the nose-wheel usually being used as a device for triggering the throwing mechanism.

(a) *Simple net barrier.* The simplest form of net used is shown in Figure 6 and appears as a wall or high fence across the runway. It consists of a pair of edge-ropes, an upper length being supported by a pair of masts (one on each side of the runway) so that the mid-point is at least clear of the canopy of aircraft with which it is to be used. A lower length lies on the ground, and the two are spliced together, near the masts, and continue as a single rope to the energy-absorbing system. Between the upper and lower edge-ropes are a series of verticals spaced at intervals of a few feet, the verticals being fixed to the edge-ropes. The edge-rope is usually made of steel or fibre rope, or maybe a combination of the two, and the verticals are of fibre (usually nylon) rope or webbing.

In operation, the nose of the aircraft passes through the net, between a pair of verticals, brushing one side if needs be. The nose wheel passes over the lower edge-rope, and the canopy under the upper edge-rope. The leading edge of the wings engage the verticals, and carry them forward, the upper edge-rope being dragged free from its supporting masts (through shear pins). Those verticals intercepted by the wings deploy above and below the leading edge of the wing, and those verticals not engaged trail loosely behind, as shown in Figure 7. From this figure it is clear that most of the retarding force is applied to the aircraft through the pair of verticals closest to

the wing tips. Therefore, unless the retarding force is small, a critical backward bending moment may be applied to the wing roots. It is to be noted also that any pair of verticals must be capable of transmitting alone the full retarding force. In an effort to distribute the loading amongst all the verticals engaged by the leading edge, the verticals can be increased in length away from the centre, but better distribution of load is then only achieved if the aircraft engages the middle of the net - a condition which cannot be specified in practice.

Webbing is probably superior to rope for the verticals, ensuring area rather than line loading of the points of engagement. Also, extensible material such as nylon, instead of steel, must be used in the construction of either the verticals or the edge-rope, or both. The reason for this will be explained more fully later; suffice for the present to say that it is essential- especially so for high engaging speeds - in order to minimise snatch loads which, without the use of an extensible material, could produce failure loading in the net.

Immediately following the engaging of the wings with the verticals at speed, the upper edge-rope is pulled violently downwards and the lower edge-rope upwards. The upper rope impacting on the mid-upper fuselage may well cause some local damage - especially if there is a dorsal fin. The lower edge-rope and the lower portion of the verticals may foul the main undercarriage struts, wheel fairings, flaps, aerials, or underwing stores. The essential extensible nylon is more easily damaged - maybe to the point of failure - than the steel, so that, whilst complete failure would result from a severed edge-rope, it is not so with a severed vertical. For this reason the verticals are made of nylon and the edge-rope of steel. The damaging effect of a plain steel rope can be reduced a little by braiding it with, say, hemp.

Thus a net as described will catch and hold an aircraft whilst it is brought to rest, and the aircraft will receive some damage. The damage will not amount to major structural damage and will be without danger to personnel on board, but there will certainly be a period of repairing before the aircraft is serviceable again.

(b) *Compound net barrier (Fig.8)*. In order to achieve more uniform loading of the wing - and this has been essential with barriers for aircraft carriers, where the short space available necessitates the use of high retardations - a multiple or compound net has been used. Here a separate rectangular edge-rope is used for each vertical - except where space is available, when a second or even a third vertical can be added, provided that they are separated by a distance greater than the span of the aircraft. The verticals are looped over the edge-rope and, except for being lightly located to facilitate rigging, are free to slide and thus take up a natural position. Such a net is suspended between masts as before and, on engagement by an aircraft, it enfolds the aircraft, as indicated in Figure 9. Strictly, this is a statically undeterminate system, but from the point of view of leading edge loading the system is superior to that of the simple net. As a result of this better distribution of load the separate verticals need not be so strong, and the intensity of local damage is not so great as with the simple net.

(c) *Barrier net for aircraft with highly swept wings (Fig.10)*. A highly swept wing aircraft needs more careful consideration, otherwise there is a danger of the vertical elements slipping off the leading edges and the aircraft passing through the net. Here the plan is to use the simple net. The two adjacent verticals, between which the

nose of the aircraft passes, together with that part of the upper and lower edge-rope joining these two verticals, forms a noose which snares the aircraft. The peripheral length of this noose or loop should not be so great that the aircraft can pass through it. Perhaps the only circumstances when this could happen would be with a small aircraft engaging a net which is primarily designed for a much larger aircraft.

(d) *Tail fin retardation.* On at least two occasions, during barrier tests in the United Kingdom, all the verticals engaging the wing leading edges were broken. The main wheels then rolled over the lower edge-rope, and the upper edge-rope impaled itself on the leading edge of the tail fin and successfully completed the stopping of the aircraft. These incidents suggest yet another barrier principle, namely the use of a simple arresting wire suspended between masts, at a sufficient height off the ground that the aircraft as a whole, with the exception of the fin, will pass beneath it - provided, of course, that the arresting forces are within the strength of the fin structure. The line of application of the arresting force is, in this position, appreciably above the aircraft centre of gravity and, for all but very small retardations, the nose-wheel will lift off the ground, but this is not critical.

(e) *Barrier masts and net operation.* The barrier nets described require supporting masts at either side of the runway and means must be provided for raising and lowering them. It is desirable for the top edge-rope to be approximately parallel to the runway and thus, on a big span, considerable tension is required to reduce sag to a small order. Although undesirable, it is permissible to use intermediate props of a frangible material. Props made of Bakelite or cardboard tubing (3 or 4 in. diameter) have been used successfully and simply break up into several pieces if struck at speed by an aircraft. Unfortunately such props do not fit into a system where lowering of the masts by remote control is used - the props having to be set up or taken down manually.

Whilst it is possible for an aircraft to taxi over a net laid on the ground, it is not a practice to be condoned, since in many forms of construction the joint between the edge-rope and the verticals may be damaged if an aircraft wheel rolls over it. For similar reasons a net must not be left laid on the ground in the touch-down area. These conditions arise where, because of space limitations, the barrier is set up near the end of a runway and not clear of the end in the over-run area.

A net usually sustains some damage after an arrest - particularly the vertical members - and therefore it should be carefully examined and repaired as necessary before being used again. This requirement dictates that a spare barrier net shall always be available for erection.

Since the barrier net is out in the open continuously, the nylon elements deteriorate slowly in respect of strength, and the nylon parts, whether used or not, should be replaced at intervals of six months. This deterioration is not completely understood and further experience might indicate an extension of the six months period.

The compound net has been used successfully with a single co-axial propeller unit. The verticals, with their individual edge-ropes, in the way of the propeller discs, are torn down and mutiliated - maybe wrapped around the propeller hubs - but the verticals on either side of the discs are left free to engage the wing leading edge. The simple net, with propellered aircraft, is however a doubtful arrangement, and maybe even dangerous.

5.2.4 *Undercarriage Retardation without the Use of Special Fittings*

We now turn to a more detailed discussion of schemes for making a conventional arresting wire engage the two main oleo struts without resort to special fittings on the aircraft. There are several ways of giving the necessary lift to an arresting wire after the nose-wheel has passed over it.

(a) *Aircraft configuration requirements.* Before schemes such as those just mentioned are considered, the aircraft configuration should be examined. No part of the aircraft forward of the main wheel struts (particularly close to the struts), except the nose-wheel, should extend below a horizontal plane which is tangential to the main wheels. Any aircraft parts that do extend below this level may interfere with a rising arresting wire; in consequence, the wire will not reach the struts, but will strike the wheel and be rolled down. Further, success is more likely to be achieved if the undercarriage strut is a simple vertical member. An aircraft with a fuselage keel line whose clearance from the ground is less than a main wheel diameter is an example of incompatability.

The United States F.86 and the Canadian CF-100, both without underwing stores, have a good configuration. The British Meteor is definitely not suitable and the Canberra and Venom are doubtful. The addition of underwing stores - particularly close to the undercarriage - may make 'catching' impossible, or at least, may seriously prejudice the chance of success - the F.86 being a particular example of this (see Figure 11). Even with a satisfactory configuration, 'catching' success may depend upon how the arresting wire is actually lifted. In this respect there are two general principles: one is where the wire is thrown or flicked upwards, and may fall (under gravity) before it engages the struts. The second is where the wire is jacked upwards and is held in the uppermost position until it engages the wheel struts. The second method is more likely to be successful but involves greater complication of ground equipment.

A few of the various methods of lifting the arresting wire will now be described.

(b) *The 'Davis' barrier.* The first device of this type was conceived and tested by the United States Navy for use aboard aircraft carriers with nose-wheeled aircraft. The device was not entirely reliable when an aircraft engaged it in free flight (i.e. not rolling on the deck) and was replaced by a net type of barrier or 'Barricade'. However, the United States Air Force adopted the scheme and developed it further and, judging by reports, used it extensively and with considerable success (especially with F.86 aircraft) in the Korean War. The functioning of this device is shown in Figure 12. An actuator strap, made of webbing, is stretched across the runway, and supported by low stanchions on either side of the runway, the strap being above the runway level by an amount approximately equal to the height of the nose-wheel strut. Attached to this actuator strap, at intervals of 5 or 6 ft across the runway, are lifter straps of similar material. These lifter straps are about twice as long as the height of the actuator strap above the ground, and the lower end is fixed to the ground a little forward of the actuator strap, the attachment being designed to break out at a required load. The slack in the lifter straps is formed into a loop and disposed as shown in Figure 12. The arresting wire passes through these loops and lays on the ground. The loop in the lifter strap is maintained by special snap fasteners or by stitching of a specified strength. In operation, the nose-wheel strut engages the actuator strap and carriers it forward. The top ends of the lifter straps on

either side of the nose-wheel, and especially the two immediately adjacent to the nose-wheel, are impulsively carried forward. The slack in the lifter strap is taken up and, the loop in it, together with the arresting wire, is lifted upwards and forwards. The slack having been taken up, the loop stitching comes under load and breaks, the lifter strap becoming slack. Further forward movement of the aircraft takes up this new slack and, in doing so, imparts yet another upward impulse to the arresting wire. That part of the arresting wire between the loops follows roughly the pattern set by the short length actually in the loop. The main undercarriage struts are all the while overtaking the rising wire and engage it. Further motion of the aircraft breaks the ground fixing of the lifter strap and the actuator strap is torn away from its attachments to the stanchions at each side of the runway. It is usual to duplicate the actuator and lift strap systems, so that, if the nose-wheel runs directly into a lifter strap (in which case it will not function correctly), then the adjacent lifter straps of the second system will function as planned. The layout of the actuator strap and lifter strap must, for best results, be matched (usually by practical tests) to the geometry of the aircraft. The lifting action is a dynamic one initiated by the engaging speed of the aircraft and as such there is a minimum speed below which, even with the most favourable configuration, the arresting wire will not be caught by the wheel struts. Below this speed the arresting wire is thrown up only feebly and falls below wheel-top level before the wheel reaches it. In this case the wheels will roll over the wire and the only resistance offered to the aircraft will be that required to pull away the lifter straps from their ground fixings and the actuator strap from its stanchion attachments. If the speed is marginal, then only one strut may be caught, with consequences as previously described. A given lifter system may function with more than one type of aircraft if they are sufficiently similar, but it may not be the best system for any one of the aircraft, with a result that the minimum functioning speed is not as low as desired.

This lengthy description outlines only briefly the mechanics of this barrier action and the detailed examination of high speed cine camera records is recommended to acquire a better understanding. The system is not amenable to mathematical analysis. Its development is essentially a practical science.

An example of how each aircraft must be studied separately is the case of the British Hunter aircraft - even without underwing stores. This aircraft has a nose-wheel door which, with the nose-wheel down, hangs down vertically a little distance ahead of the nose wheel, and which, when viewed from ahead, masks most of the nose-wheel strut. Remove this nose-wheel door and the system appears to work well at speeds above 35 knots. However, with the door in its normal position it (instead of the nosewheel strut) engages the actuator strap and the lifting action is initiated too soon, with the result that the arresting rope has fallen down to too low a level by the time the main wheel struts overtake it. Nevertheless, if the actuator is engaged at a sufficiently high speed the nose-wheel door will be carried away and the actuator strap then engages the nose-wheel strut and the lifting action is completed effectively. The collapse of the nose-wheel door varies both with the speed of engagement and with the distance of the point of impact below the door hinge-line.

This barrier is an efficient and effective one within its limitations and it is important to recognise and establish these limits, otherwise an operator (and pilot) may be given a false sense of security and the system will fall into disrepute.

There are a number of variations of design of the lifter strap, the variations being used in an endeavour to obtain better lifting action at low speeds, to make them usable with more than one type of aircraft; and to simplify construction, assembly and replacement after use.

(c) *British airfield barrier Mk.2.* The troubles described with the Hunter nose-wheel door led to a design whose object was, as before, to lift an arresting wire into the path of the main wheel struts after the nose-wheel passed over it. The barrier is illustrated in action by Figure 13. It consists of a top span of steel rope, supported by masts at each side of the runway so that it is well clear of the top of the fuselage. Suspended, at 5 or 6 ft intervals, from the top span are a series of vertical wires terminating in a loop at ground level through which the arresting wire passes. In operation, the nose of the aircraft passes between a pair of verticals, brushing one aside if it is too close, and the leading edge of the wings (first at the wing roots) engages the verticals. This impact impulsively draws the upper end downwards and lower end (together with the arresting wire) upwards (Fig. 14). This lifting action on the arresting wire propagates away on either side, especially so with some initial tension in the wire, so that it is raised above wheel level in the track of the main wheels.

Further motion of the aircraft tears the top span from breaking links at the mast heads, and the top span and verticals trail loosely behind and over the aircraft. The crux of the problem was to get the arresting wire lifted to a sufficient height in a sufficiently short space of time. To ensure this several features must be achieved: there must be no slack whatsoever in the verticals, and to achieve this they are individually adjusted in length so that the lower loop, carrying the arresting wire, is just clear of the ground, otherwise valuable time is lost in taking up the slack before lifting action is imparted. The arresting wire should be as light as possible and be initially under tension. The top wire should be as heavy as possible, in order to resist downward yielding and so enhance the upward lift at the lower end; and the verticals should be made of steel rope and not fibre.

Successful trials have been made at speeds between 14 and 97 knots.

As a result of trials, this barrier has been adopted for limited service use, but at the time of writing no reports of its being called into action are available. The height of the barrier is considered to be an undesirable feature but, being of all-steel wire-rope construction, it withstands deterioration much better than nylon systems.

(d) *Pressure-operated jacks for lifting an arrester wire (Fig. 15).* With the object of keeping the above-ground equipment as simple as possible, the following scheme has been the subject of trials: a simple arresting wire is laid on the ground and directly beneath it, at 4 or 5 ft intervals, are gun or jack units, the pistons of which bear on the underside of the arresting wire and are also attached to it. The jacks can be energised by either cartridges or compressed air, so that at a given signal they are all fired simultaneously and the rope, with the pistons attached to it, is flung into the air and will engage the undercarriage struts provided that the aircraft configuration is suitable and provided that the firing signal is timed correctly. The firing signal can be initiated in several ways; for example, by the nose passing over a weight-sensitive pad set in the ground, or the nose strut engaging a wire stretched across

its path. The short period of time during which the arresting wire is lifted is constant (depending only on the gun characteristics). If, as is required, the wire has to arrive at the required height simultaneously with the arrival at the wire of the main wheel struts, for all possible speeds of the aircraft, then a time factor (depending upon aircraft speed) must be fed into the firing circuit between the aircraft triggering the circuit and the guns firing. Thus a special measuring and computing device is necessary. Whilst such a device is considered to be possible, the complications involved do not seem justifiable in view of the alternative schemes. It is believed that such schemes have not progressed beyond an experimental stage.

(e) *Aircraft-operated jacks for lifting an arresting wire (Fig. 16).* Another scheme with very simple above-ground arrangements involves jacking struts set in the ground immediately below an arresting wire which is laid on the ground. The jacks may be set vertically or inclined so as to push the wire upwards and forwards. An actuator strap is stretched across the path of the nose-wheel unit and lifter straps, at regular intervals, connect the actuator strap to the lower end of the jacking struts. Thus, when the nose-wheel unit carries forward the actuator strap, the jacking struts raise the arresting wire into the path of the main wheel struts. The struts are stopped at the top of their travel by oleo units and the lifter and actuator straps break loose, leaving the arresting wire supported on the now stationary struts.

This scheme appears most attractive. It will obviously work at low speeds and the upper speed limit must necessarily depend upon detail design, inertia loading and impact phenomena being most important factors. To illustrate the dynamic nature of the problem, assume an aircraft with 2½ ft diameter main wheels and a wheel base of 17 ft engaging the barrier at 100 knots. The jack struts must be raised in less than 0.1 sec. If the strut is accelerated uniformly over the first half of its stroke, and uniformly retarded over the second half, then it will achieve a maximum velocity of 50 ft/sec under an acceleration of 30g. As a result of giving the arresting wire an impulsive upward movement at a number of separate points along its length, the wire between these points will be set vibrating in a vertical plane. The amplitude of this vibration is difficult to predict but must necessarily influence the height of jack strut required. Practical tests are thus an essential part in the process of design.

(f) *Aircraft-operated levers for lifting an arresting wire (Fig. 17).* Both of the last two schemes described require pockets to be formed in the runway to accommodate the gun or jack strut units. With the object of avoiding such pockets, which may have a depth at least equal to the diameter of the main wheels, several proposals have been made which might well be described as 'lever' schemes. Here, a series of arms or levers of a length at least equal to the diameter of the main wheels are laid on the runway (or in shallow recesses) in a fore-and-aft direction. The forward end of each arm turns on a pivot fixed to the ground and the after end of the arm supports the arresting wire in a crutch or clip arrangement. As before, an actuator and lifter straps are used, the lower end of the lifter strap being attached to the arm; in operation this causes the arm to swing up in a vertical fore-and-aft plane. There are several variations of this scheme; the wire may free itself from the arm on an upward path or it may be retained on the arms, the arms being checked in a near vertical position and the wire torn from the arms by the main wheel struts.

(g) *Pressurized hose arresting pendant.* Another scheme - as yet untried - is to replace the steel rope arresting wire by a rubber-lined fabric tube, located and

trapped in a narrow groove formed in and across the runway, the hose being inflated with air. Actuator and lifter straps would again be used, the lifter strap passing under the trapped hose and fixed to the ground aft of the hose. In operation the lifter straps, under tension by virtue of aircraft engagement, would jerk the hose out of the groove and with its automatic resumption of a circular cross-section there would be a release of strain energy of the air within, which will 'bounce' the hose upwards, leaving it to engage with the main undercarriage struts.

5.2.5 *Operation of Barrier Masts*

Operationally it is most desirable that the raising and lowering of barrier masts may be controlled remotely by personnel in the airfield control tower. The more enthusiastic advocates even suggest that the masts should be capable of operation by a pilot, as and when he requires the barrier. Both schemes are possible, but the pilot-operated one is likely to be complex.

Barriers, if in the 'up' position while aircraft are taking off, present a hazard, particularly with the high barrier nets. If a pilot abandons a take-off, it should be possible to raise the barrier within a few seconds. The design of the masts, their operating mechanism, and the aircraft catching system should be such that, in moving into the 'up' position, the catcher system assumes its correct configuration without the necessity for close inspection and arranging parts of it manually. The raising and lowering should be possible under all possible weather conditions. These various design details are all important and call for careful consideration.

If, however, a simple arresting wire is used in conjunction with aircraft fitted with conventional arresting hooks, then all the foregoing design problems disappear and the severe requirement that the over-run device is to be under the control of the pilot is satisfied in that the pilot simply lowers his hook.

This completes the outline of catching devices. It is believed that a number of people in various countries are working on the problem, but the number is only relatively small and the amount of information published is only meagre. It may be that most of the people are working on similar lines - may be someone has devised, or might soon do so, a scheme with fewer limitations and of wider application than those that have been described.

5.3 Energy Absorbers

5.3.1 *General*

For a complete over-run installation, any of the catching systems described must be coupled to an energy absorber. Each end of a net or arresting wire can be connected to separate absorber units, usually located one on each side of the runway, each designed to absorb approximately half the energy of the aircraft. Alternatively, the two separate ends can be brought to a single absorber unit. There are advantages and disadvantages with both layouts.

In many respects the absorber problem is simpler than the catching problem; for example, it is independent of the configuration of the aircraft.

Many, but not all, of the energy absorbers to be described are machines where good serviceability is best ensured by regular use. It is hoped by all concerned that these energy absorbers will not be in regular use, but when the need for them does arise they should function correctly. This particular requirement merits most careful consideration, especially for airfields located in regions where extreme weather conditions may prevail.

There are a number of types of unit that have been made and used, and there are variations of these, as well as proposals that are yet untried. Brief descriptions will be given of six devices, to indicate broad principles, but it is to be emphasised that design detail plays an important role in all cases.

5.3.2 *Hydraulic Ram and Cylinder Energy Absorber (Fig. 16)*

This unit is described first because most experience, derived from its use on naval aircraft carriers, is available with it.

A pair of wire ropes is reeved about two sets of pulley blocks which are separated by a ram and cylinder unit. One end of each rope is anchored and the other ends are connected to each end of the arresting wire or barrier net. As the aircraft carries its catching device forward, rope is drawn from the jigger unit and equal amounts are paid out to each side of the aircraft. This drawing-off of rope drives the ram into the cylinder and expels hydraulic fluid into an air-loaded accumulator via a non-return valve and a pressure generating orifice. By metering this orifice area according to the cross-head movement, suitable hydraulic resistance is generated, which is communicated to the rope (the main reeve) and thence to the aircraft.

For airfield work two separate jiggers could be used - one on each side of the runway. Reeving ratios of up to 20/1 can be used and more than a single unit, or a single pair of units, may be used, if necessary, to break down the gear into smaller components.

To re-set the units the non-return valve is by-passed by the hydraulic fluid in the accumulator, under the influence of the air pressure above it.

The gear can be used repeatedly in rapid succession without developing an excessive temperature rise.

5.3.3 *Drag Chains*

These have been used with considerable success. They are simple, reliable, and need negligible maintenance (if any). The chief disadvantage is their weight - the total being some two or three times the weight of aircraft to be stopped. Thus, after an aircraft has been stopped, heavy towing equipment is required to get the chains back into place.

Figure 20 shows the more usual arrangement of the chain; a length is connected to each end of arresting wire or net and then laid in a straight line down each side of the runway on the forward side of the wire.

In operation the aircraft, via the 'catcher', drags each link into motion in rapid succession, the chain thus streaming along the ground in the wake of the aircraft. The momentum of the aircraft is transferred to the chain and the kinetic energy acquired by the chain is dissipated as heat through friction between the chain and the ground.

The presence of the chain on the runway is undesirable and precludes the use of runway lighting in any area over which the chains may sweep.

Figure 21 shows an arrangement of chains that does not sweep on to the over-run area but it does require a pair of deck edge sheaves and long lengths of steel rope. Also, with this arrangement, re-setting of the chains will be somewhat simpler.

The performance of a drag chain system is difficult to calculate, since it involves the solution of a complex second-order differential equation. However, Bullen[6], with the use of some simplifying assumptions, has produced some useful performance curves which experience has shown to be reasonably reliable. Recently McLeisch[3] has also produced some performance curves.

With chain of uniform line density, the variation of retardation with run-out shows a rapid rise to a peak value, after which the retardation falls away progressively, thus giving only modest retardation efficiencies. This efficiency can be improved by increasing the line density of the chain progressively towards the tails of the chains, either by changing to heavier chain or by using extra lengths of chain in parallel.

In considering aircraft of about 25,000 lb at speeds of 100 knots, chain with a line density of the order of 100 lb/ft is required. The strength of such chain is more than adequate, its line density and flexibility being the properties used. Since chain of the order required is expensive, a satisfactory substitute can be used in the form of suitably shaped cast iron blocks threaded on a steel wire rope. These blocks consist of short hexagonal prisms with a hole down the axis, the blocks being separated by spherical cast iron beads, as shown in Figure 22. This chain, when made up in lengths of about 20 ft with standard rope sockets at each end, can be coupled together in series or in parallel as required.

5.3.4 Rope Drums with Friction Brakes (Fig.23)

In this scheme a length of steel rope is led off from each end of the 'catcher' and is wound on a drum or reel mounted on a shaft in bearings, and the unit is firmly fixed to the ground, with one drum on each side of the runway.

In operation the aircraft draws rope off the drums and resistance is developed by means of a friction brake. The unique feature here is the exceptionally high rate of dissipation of energy. The design of such a brake should follow modern aircraft multi-disc wheel brake practice, i.e. a large friction area operating at a low intensity of loading. If this feature is ignored, extremely high surface temperatures, admittedly of only brief duration, will occur, with a risk of failure. The temperature falls away very rapidly below the rubbing surface and cracking and warping, leading to erratic operation, may result. The discs must therefore be made thin.

The inertia of the drums and all the moving parts attached to them, such as the rope and brake discs, should be as light as possible, in order to minimise snatch loads when the drums are accelerated violently into motion on engagement by the aircraft.

To achieve minimum inertia it is usual to coil the rope on the drum in more than one layer - three layers have been used. In such a case the rope must be laid up most carefully - the coils tight and packed close together. If this feature is not observed there is a risk, when drawing off the top layer, that the rope may be pulled down and jam in between two coils immediately below it, with a risk of damage to the rope.

To minimise the initial snatch loads, the brake loading should be applied progressively, the full pressure being developed by the time that the drum has reached maximum speed.

The brakes may be loaded pneumatically by bleeding air from a bottle, through a suitable restriction - the bleeding being initiated by the initial rotation of the drum. Or loading may be done hydraulically using, say, a pump driven by the rotation of the drum.

A brake unit of this type cannot be used repeatedly without extracting a substantial proportion of the heat between each operation, and this will take an appreciable time.

Because of the difficult friction brake problem, it has been proposed that the drum should be loaded by a hydraulic gear pump. To meet typical arresting requirements, such a pump would have to have a peak absorption rate of the order of 4,000 h.p. and would scarcely fit into a reasonable design.

5.3.5 *Friction Rail Scheme (Fig.24)*

This scheme neatly avoids the drum inertia and the rotary brake heat problems of the previous scheme.

Instead of coiling the rope on a drum, it is laid out in a straight line and to the tail ends is attached a small box-like unit in which are mounted friction pads which can be loaded with pressure. In operation, this friction box is dragged along a flanged rail or over a long steel strip, the friction pads being clamped to a flange or strip under pressure. The frictional resistance developed is then transmitted to the aircraft by the rope.

In this arrangement a much higher intensity of loading of the friction pads (and thus a smaller area) is permissible than with the multi-disc rotary brake. Very high rail-surface temperatures of momentrary duration will be developed, especially with the friction box travelling at maximum speed. The heat thus deposited on the surface of the rail or strip is quickly absorbed by the bulk of the metal in the rail or strip, with only a nominal rise in overall temperature. Thus, if necessary, the gear could be operated several times in rapid succession.

Such a brake rail has a much higher heat capacity than the multi-disc brake and a much larger exposed area from which heat can be dissipated by radiation.

5.3.6 *Undrawn Nylon*

A rope made of undrawn nylon fibre has the property of extending some 250% to 300% when loaded to failure (Fig.25). A large proportion of the extension is plastic and, after a relatively small extension, the load up to failure rises only slowly. In loading

a rope to failure, energy is absorbed as heat by the nylon at a rate of at least 35,000 ft lb per lb of rope. If the rope is unloaded before failure is reached, there is an elastic recovery of only 2,000 ft lb per lb of rope.

Thus if two ropes of suitable length and weight are attached, one end to each end of the 'catcher' and the other ends to ground anchorages, we have a very simple arresting device. However, as the aircraft comes momentarily to rest at the most forward point of its run, the elastic energy stored in the rope will be returned to the aircraft, thus rolling it backwards.

This recoil energy can be reduced to an acceptable minimum by replacing the pair of heavy ropes by a pair of groups of smaller ropes, each group being made up of a number of ropes of differing lengths in parallel. One end of each group is anchored to a common ground fixing, and the other ends are attached at intervals along a steel 'carrier' rope. One end of the carrier is attached to the 'catcher' element and the other end to the last group of undrawn nylon (Fig.26).

The 'carrier' rope is snatched forward on engagement by the aircraft and resistance is offered as the first group of nylon ropes is stretched. The ropes within this rope are of different lengths and therefore break successively and not simultaneously. During this period of successive breaking the extension of the ropes is such that the 'carrier' rope now starts to meet resistance from the second group of ropes and, as the load builds up from this group, loading by the first group is removed as its ropes fail. Thus, as the aircraft comes to rest, the elastic energy available in the loaded but as yet unbroken ropes is only small and the aircraft will roll backwards, if at all, very gently. Figure 27 is a diagram of an undrawn nylon pack. In practice the nylon ropes and carrier rope are packed in a canvas case in which suitable pockets are formed, somewhat after the fashion in which the shroud lines of a parachute are packed. The arrangement is usually referred to as undrawn nylon energy-absorber pack. By suitable arrangement of the groups, and of the ropes within the groups, the pattern of resistance can be varied as desired.

The performance of the packs is consistent, especially so if the ropes are damp. Unfortunately, reliability deteriorates if the temperature of the ropes falls below freezing point and the ropes fail before 300% drawing is completed.

The absence of rigid inertia parts prevents the development of high snatch loads on first engagement. Cost is the chief disadvantage of the undrawn nylon rope scheme. The rope costs about 25 shillings a pound and the cost of making up and packaging is about the same amount. Thus packs to stop a 30,000 lb aircraft at 100 knots would contain about 400 lb of rope and would cost £1,000.

5.3.7 The Water Squeezer Energy Absorber

This is a novel, simple and effective gear which has been designed and developed by All American Engineering Company, Wilmington, Delaware, U.S.A.

From each end of the 'catcher' a long steel rope passes into a long straight tube through a plain long close-fitting gland, and the free end of the rope carries a simple piston. The tube, which is filled with water, has a diameter at the rope entry end which provides a running clearance to the piston, whilst the bore of the tube at the other end is appreciably greater than the diameter of the piston. The bore of the

tube is varied gradually from one end to the other; for ease of construction the variation is achieved in steps, although theoretically a continuous variation is required.

In operation the piston is drawn through the tube and the water is transferred from one side of the piston to the other through the annular clearance between the piston and the tube wall. As the piston slows down in its progress along the tube, i.e. in phase with the slowing down of the aircraft, the annular clearance becomes less, such that the fluid velocity through the clearance is substantially constant, thereby developing a constant fluid pressure on the piston. This statement is not strictly true, especially in the first part of the piston travel, when the rope experiences considerable drag from fluid friction as it is dragged at speed through the stationary fluid.

The tubes can be laid on the ground or may be buried, so as not to present an obstruction and as a protection against frost. The bore of a typical tube varies from 4½ to 7½ in. The water in such a tube has a large heat capacity and thus the gear can be used repeatedly without any fear of overheating. The piston is provided with a light tail rope which is used for re-setting the gear.

It is probably true to say that hydraulic gears give more consistent performance and can be used more repeatedly than gears using the property of dry friction. However, with the recent advances in friction material techniques, particularly in aircraft wheel brakes, more uniform performance is now better achieved.

The choice of gear must necessarily depend on many factors, such as whether it is to be a permanent installation or a temporary one, the nature of the site, and whether or not the components must be easily transportable.

6. THE MECHANICS OF ARRESTING GEARS AND SAFETY BARRIERS

To do justice to this subject would require a separate paper, but it is considered that a useful purpose would be served in stating, without proof, some of the more important points of such a paper.

The use of ropes and similar elements which have mass and elasticity leads to complex mathematical processes when analysing an arresting system theoretically and, whilst elasticity can often be neglected without serious loss of accuracy at low engaging speeds, it is of a first order of importance at high speeds - certainly at speeds above 100 knots.

With a conventional arresting hook and arresting wire, the mechanics of such a system are fairly well developed but, when nets are used which necessarily involve some initial slack in the system and where materials of differing mass density and elasticity are involved, theory at present can do little more than make qualitative pointers to critical performance characteristics. Unfortunately critical tensions usually occur soon after engagement is made, and before the speed of the aircraft is significantly reduced. Thus, if failure occurs the consequences to the aircraft are the same as if an over-run device had not been used.

Most arresting problems can be reduced to the diagrammatic form shown in Figure 28 for first-approximation calculations. All the mass of the moving parts of the ground gear can be reduced to an equivalent mass E on the ends of a weightless inextensible string connecting the aircraft to the energy absorbers.

Two important results are then obtained:-

The rope tension at the aircraft is

$$T = \frac{M/2}{1+\frac{E}{M}\sin^2\phi}\left[\dot{x}^2\frac{E}{Mlg}\cos^3\phi + P\right] \qquad (1)$$

The retardation of the aircraft is

$$\frac{\ddot{x}}{g} = \frac{\sin\phi}{1+\frac{E}{M}\sin^2\phi}\left[\dot{x}^2\frac{E}{Mlg}\cos^3\phi + P\right] \qquad (2)$$

At the instant of engagement, $\phi = 0$ and $\dot{x} = V$, the engaging speed, Equation (1) reduces to

$$T_0 = \tfrac{1}{2}\left[V^2\frac{E}{lg} + PM\right] \qquad (3)$$

and if P, the resistance developed by the gear at this instant, is equal to 0, Equation (3) further reduces to

$$T_0 = \frac{V^2E}{2lg} \qquad (4)$$

This tension, under some conditions, and within the limits of the simplifying assumptions, may well be the maximum tension, so that, in order to minimise it for a given engaging speed, E, *the equivalent mass of the moving parts of the gear, should be as small as possible and the span should be as large as possible.*

It can be shown that the weight of rope to be paid out is directly proportional to the kinetic energy of the aircraft, for a given stress level in the rope. The rope may be long and thin for long run-outs and low retardations, or it may be short and thick for short run-outs and high retardations. This rope is often a significant part of the equivalent weight. Thus a high quality rope and the least possible factor of safety is used, to minimise its weight.

The length of rope between the rendering points and the aircraft ($r = l \sec\phi$) is increasing at a rate given by:

$$\dot{r} = \dot{x}\sin\phi \qquad (5)$$

and thus builds up from zero.

With a barrier net, the aircraft on engagement tears it loose from the supporting masts and the whole link between the aircraft and the absorber becomes slack. As the aircraft progresses forward this slack is taken up and not until then is an appreciable tension set up; thus there is no paying out of rope from the energy absorber unit (see Figure 20). At the instant that the slack is taken up, the aircraft is demanding rope at a rate of $\dot{x} \sin \phi$, yet none is being paid out by the absorber unit. This difference in velocity results in a considerable impact loading of the system. The demand for cable by the movement of the aircraft, not being provided instantly by the absorber unit, is satisfied by the rope stretching under tension (possibly very severe tension). This tension force then sets the absorber in motion to provide the demand for rope and thereafter the tension falls off rapidly, except in so far as it is modified by the resistance P, which is then developed within the absorber.

ϕ_0, in the expression $\dot{r} = \dot{x} \sin \phi_0$, is a measure of the initial slack and, in a poorly designed system, particularly so if the span $2l$ is small, ϕ_0 may easily reach a value of 30°.

The high stiffness of a steel rope is such that it cannot stretch sufficiently to provide the demand without developing excessive tensions, except for small engaging speeds and small amounts of slack. It is for this reason that nylon rope and webbing (with its relatively low stiffness) is used so extensively in the construction of barrier nets, the ratio of the extensions of nylon and steel ropes of the same strength and for the same loading being about 40 to 1.

When engaging speeds are high, particularly over 100 knots, the simpler theory outlined previously leaves much to be desired and one must take account of the elastic properties of ropes and the fact that tension changes in any one part of the system are not transmitted instantaneously to other parts of the system, i.e. the sonic velocity in the rope must be considered. The overall effect of considering these properties is that a complex tension vibration is set up in the rope system, which is in effect superimposed on the tensions established by the simpler theory. A point of prime importance is to determine the maximum tension in this system, although its duration may only be of the order of 0.01 sec.

If a point in a straight length of rope is suddenly carried forward, say by impact, with an aircraft, along a line normal to its initial position, then a tension wave is initiated at the point of impact and propagates along the rope at each side of the point of impact with the sonic velocity appropriate to the rope. It can be shown that this tension has a value of

$$T = v^{4/3}\left(\frac{k}{2}\right)^{2/3}\frac{m}{g} \qquad (6)$$

where v = impact velocity

k = velocity of sound in the rope

and m = the line density of the rope.

The initial impact tension given by Equation (6) will build up as the tension wave front is necessarily reflected at various points in the rope and/or net system.

Thus
$$T_{max} = nv^{4/3}\left(\frac{k}{2}\right)^{2/3}\frac{m}{g} \qquad (7)$$

where n is a reflection factor whose value is rarely, if ever, less than 2, and may reach 5, according to the detailed design of a particular system. If then we put T_{max} equal to the ultimate strength of the rope we can determine the engaging speed which will produce failure:-

$$V_{crit} = \left(\frac{T}{m}\,\frac{g}{n}\right)^{3/4}\left(\frac{2}{k}\right)^{1/2} \qquad (8)$$

For a rope of a given material, T/m and k are constant and independent of the diameter of the rope; so, from Equation (8), we note the important fact that the critical velocity is independent of the size of the rope, and failure of a rope may not necessarily be prevented by the use of a heavier rope of the same material.

For a good quality steel rope, T/m equals 55,000 ft and k equals 10,000 ft/sec, while for a drawn nylon rope T/m equals 65,000 ft and k equals 2500 ft/sec. Thus the critical impact velocity for a nylon rope is more than twice that for steel, assuming that the reflection factor n is the same for the two ropes.

Thus, again, the superiority of nylon compared with steel has been proved. Unfortunately nylon will not withstand abrasion as well as steel, since its strength collapses if, through chafing action, the temperature of the rope is raised to more than 200°C.

The evidence on whether to use a pair of energy absorbers, one on each side of the runway, or a single unit is not conclusive. With a single unit equal amounts of rope are paid in to the ends of the 'catcher'. Many years ago, when operating tail-wheeled aircraft aboard carriers, it was established that the single unit was the better, particularly in preventing an aircraft that landed off-centre deviating more off-centre as the arrest took place, with the possibility of tracking over the edge of the deck. As a result, single units have become accepted practice, although nose-wheeled aircraft might well react somewhat differently.

A pair of separate units does not necessarily pay out equal quantities of rope end, in the case of a tail wheeled aircraft with arresting hook engaging an arresting wire off-centre, and provided with drag chains, the aircraft will swing farther away from the centre line. It may even swing off the runway and pass over the tail end of the chain if the initial off-centre distance is great.

An aircraft engaging off-centre with a net rigged with independent drum units appears in general to follow its initial direction, generally accompanied by a yawing oscillation.

Although the problem of off-centre engagements and the superiority of single or paired absorber units is not completely understood, particularly in respect of directional stability, this does not appear to be a point of importance.

7. CONCLUSIONS

Service use of over-run control devices is so limited at present that firm conclusions cannot be made, but an expression of opinion seems to be justifiable.

Soft ground over-run areas cannot be regarded as offering anything approaching a satisfactory solution to the problem.

If over-run control is to be tackled seriously, the best solution is to fit the aircraft with an arresting hook, after the fashion of carrier-borne aircraft, and install on the ground a conventional arresting wire in conjunction with a 'Water Squeezer' energy absorber.

If a conventional arresting hook cannot be fitted to the aircraft, the following points are made.

For large aircraft, undercarriage retardation seems most suitable, provided that the aircraft configuration is suitable. The arresting wire lifting mechanism needs more detailed examination.

If the large aircraft have not a suitable configuration for undercarriage arresting, there is no alternative to a net.

For small aircraft of the fighter class, with underwing stores, a net seems to be the best choice.

If ease of transportation and quickness of installation are of first importance in the choice of energy absorber units, the rotary-brake type would be first choice, although it is considered to be inferior to the 'Water Squeezer' in functional respects.

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TABLE I

Retardations (in 'g' units) for Different Engaging Speeds
and Stopping Distances

Engaging Speed (knots) \ Stopping Distance (ft)	100	200	300	400	500	600	700	800	900	1000
20	0.18g	0.09g	0.06g	0.04g	0.04g	0.03g	0.03g	0.02g	0.02g	0.02g
40	0.71	0.35	0.24	0.18	0.14	0.12	0.10	0.09	0.08	0.07
60	1.60	0.80	0.53	0.40	0.32	0.27	0.23	0.20	0.18	0.16
80	2.84	1.42	0.95	0.71	0.57	0.47	0.40	0.35	0.31	0.28
100	4.43	2.21	1.43	1.11	0.89	0.74	0.63	0.55	0.49	0.45
120	6.38	3.18	2.13	1.60	1.28	1.06	0.91	0.80	0.71	0.64
140	8.68	4.33	2.90	2.17	1.74	1.45	1.24	1.09	0.97	0.87
160	11.3	5.63	3.78	2.83	2.26	1.89	1.62	1.42	1.26	1.13
180	14.3	7.17	4.78	3.53	2.87	2.39	2.05	1.79	1.59	1.43
200	17.7	8.83	5.91	4.43	3.54	2.95	2.53	2.21	1.97	1.77

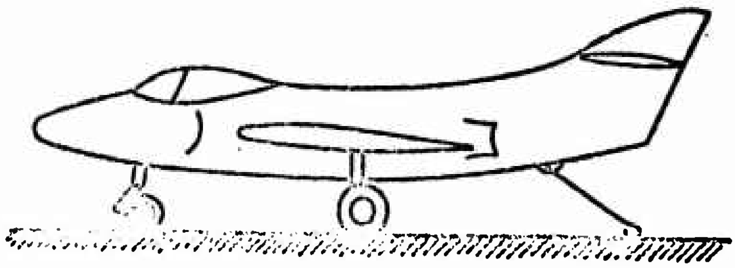


Fig.1 Arresting hook installation typical of naval carrier-borne aircraft

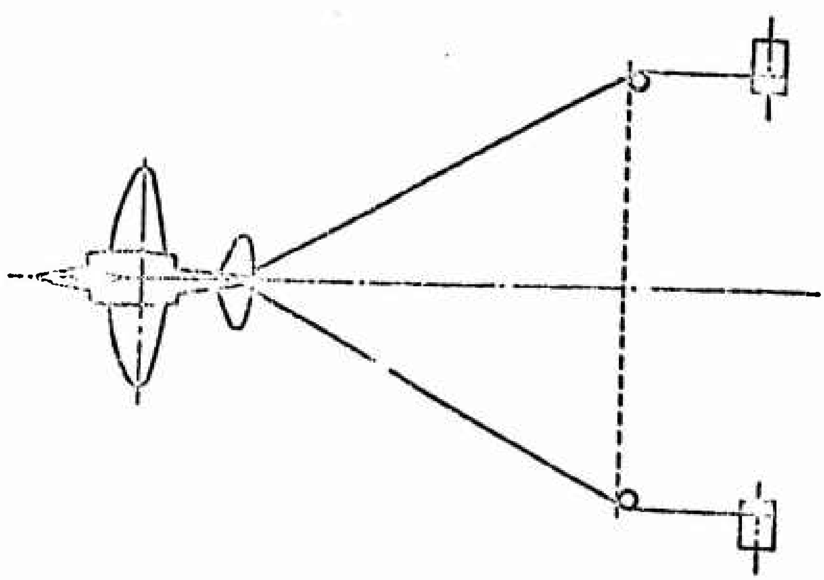


Fig.2 Arresting with conventional arresting hook

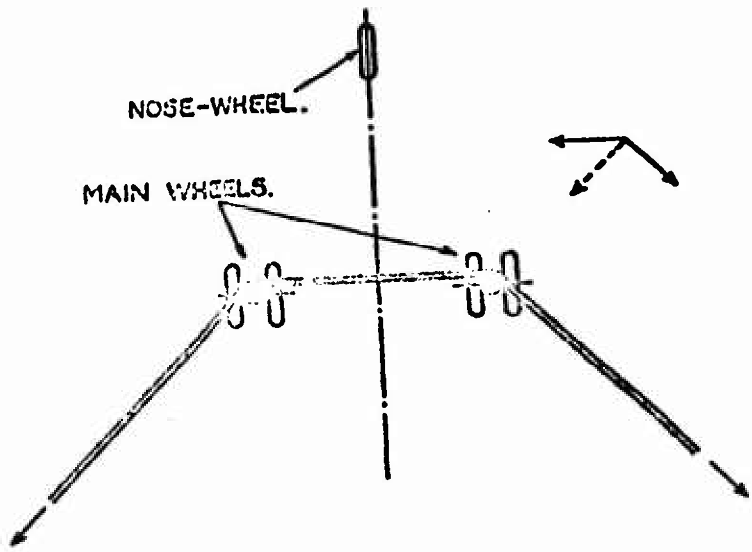


Fig.3 Plan configuration of undercarriage arresting

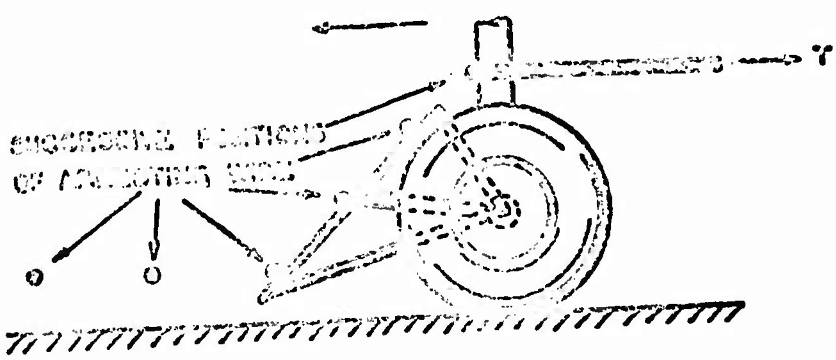
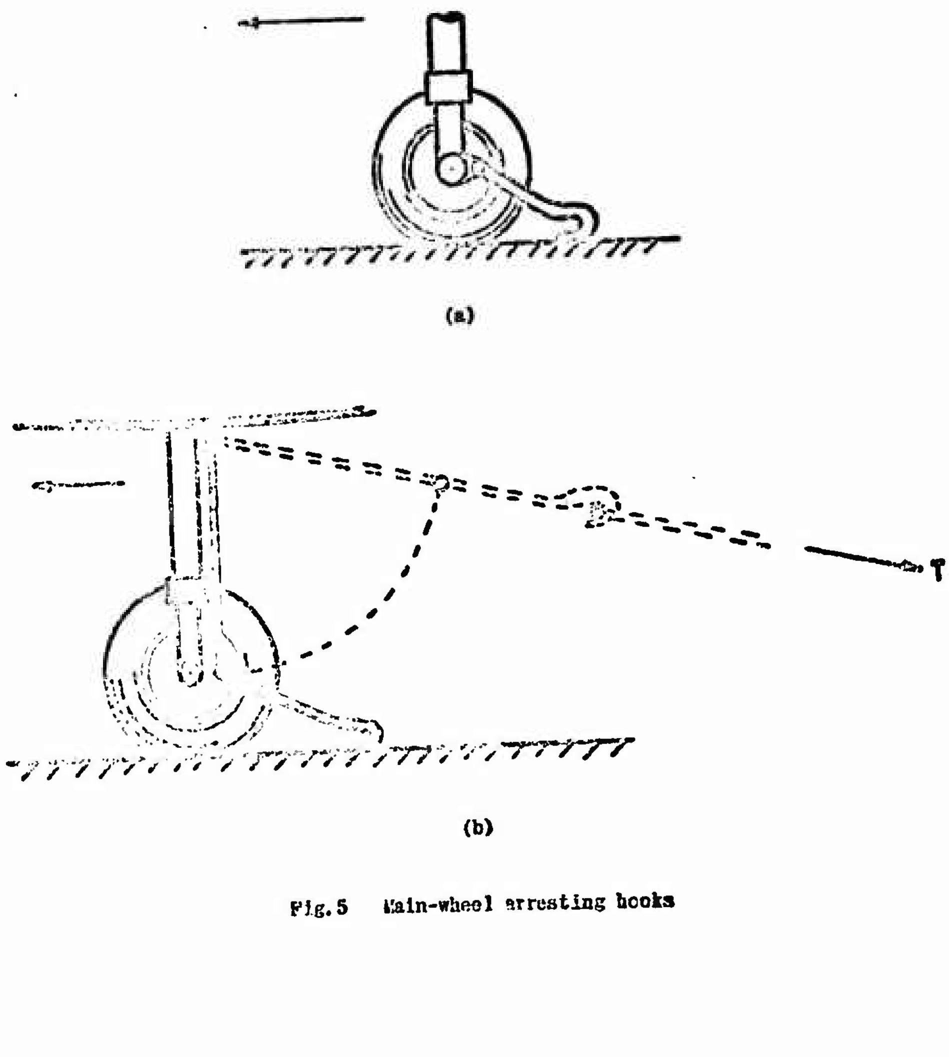


Fig.4 Arresting wire scoops



(a)

(b)

Fig. 5 Main-wheel arresting hooks

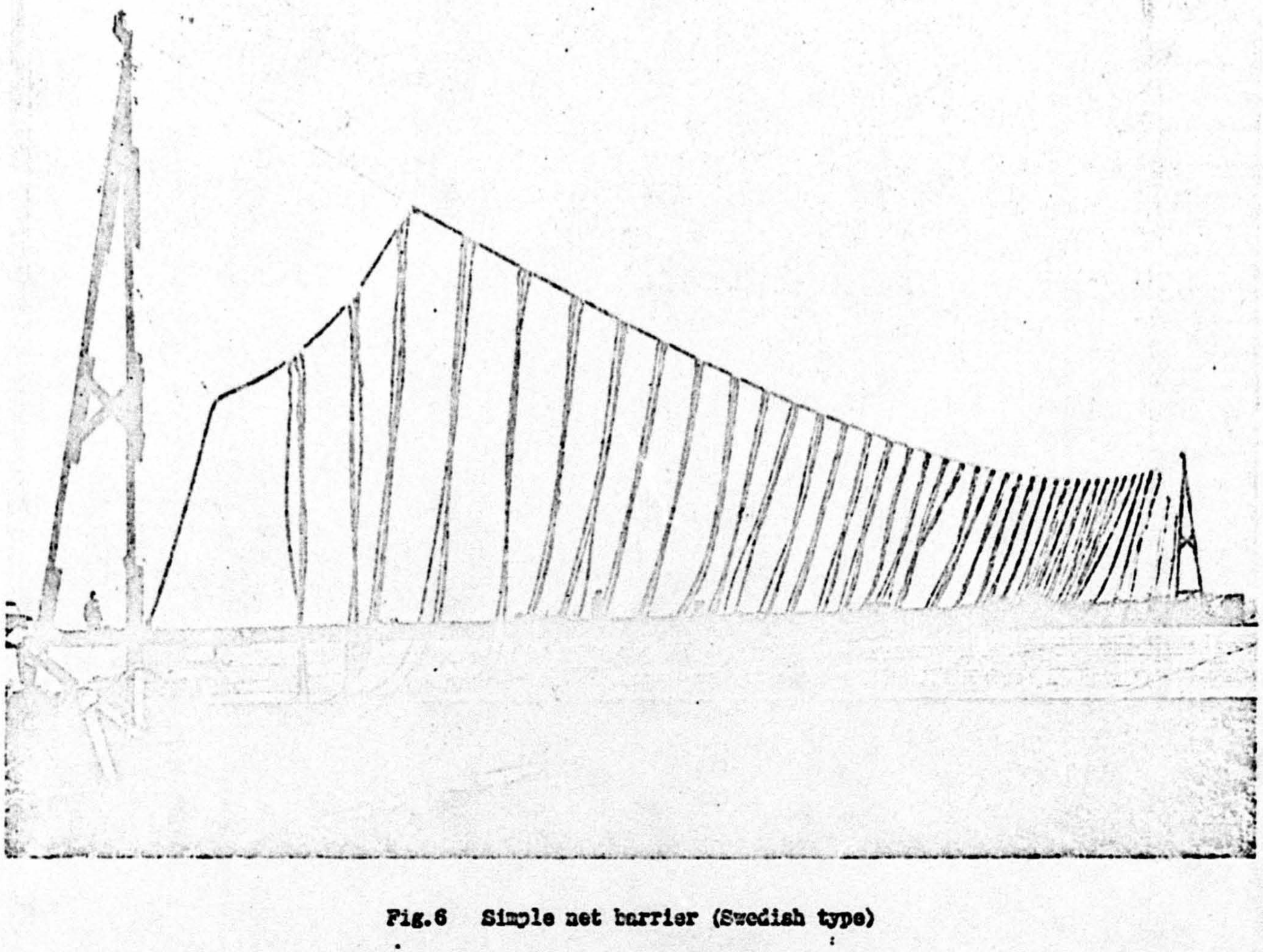


Fig.6 Simple net barrier (Swedish type)

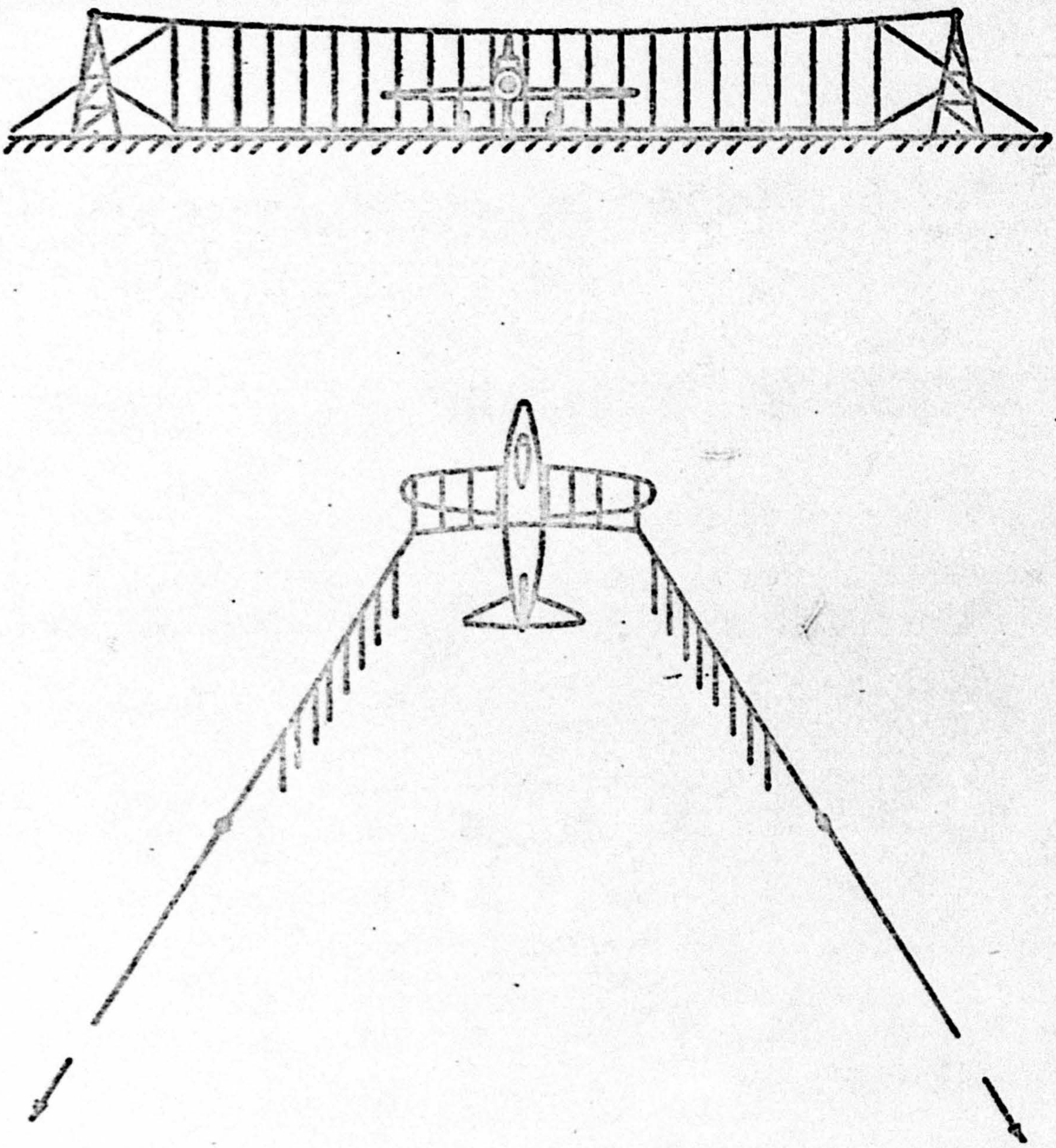


Fig.7 Aircraft engagement with a simple net barrier

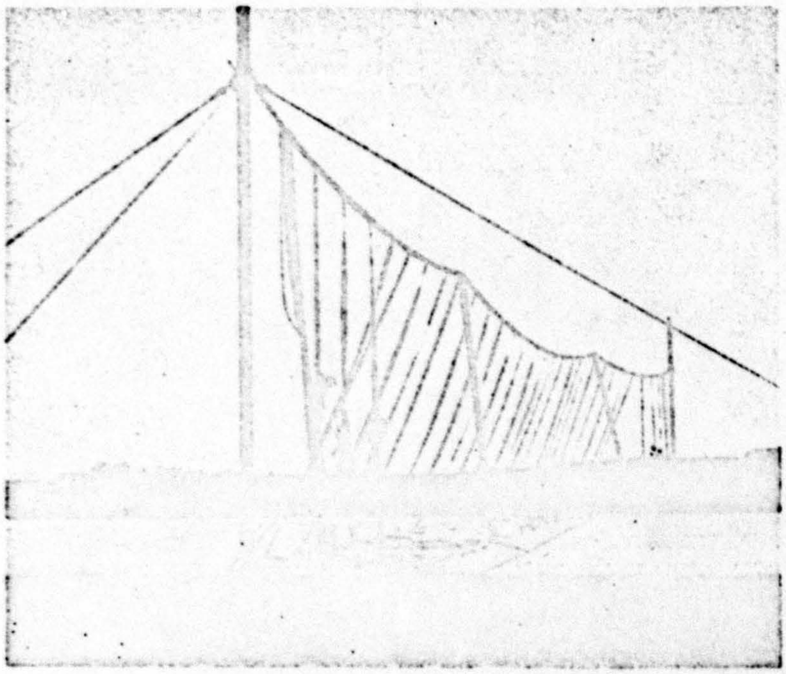


Fig.8 Compound net barrier

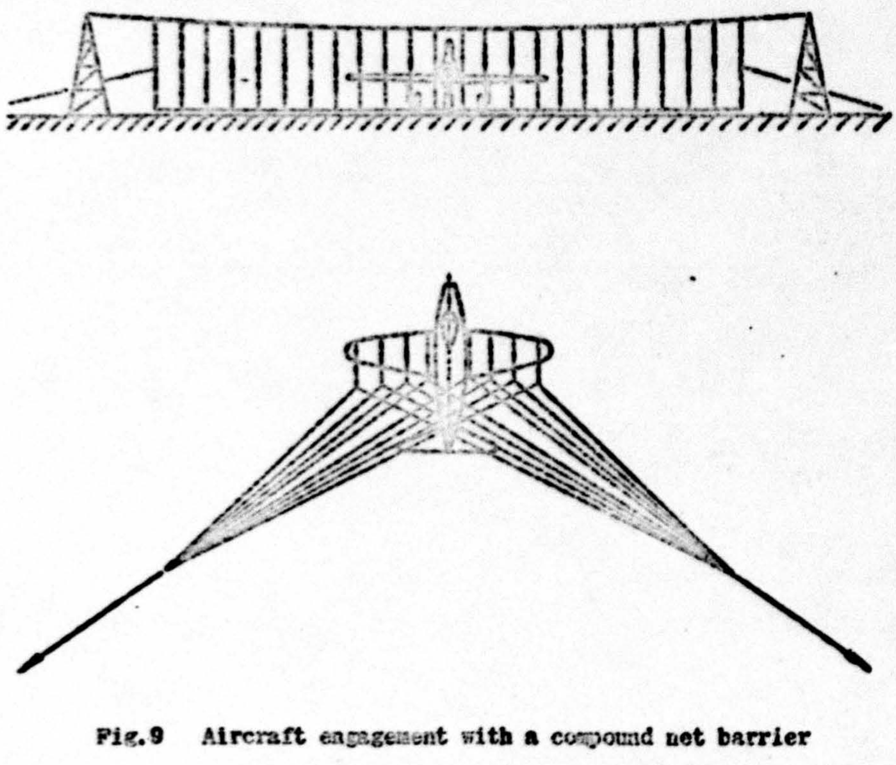


Fig.9 Aircraft engagement with a compound net barrier

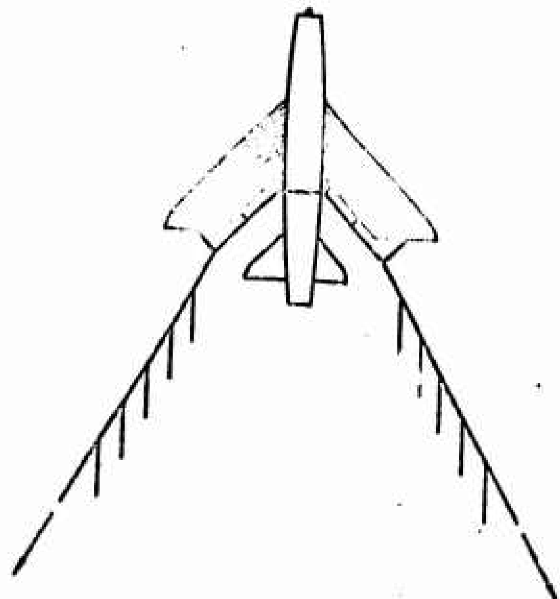


Fig.10 Barrier net for highly swept wing aircraft

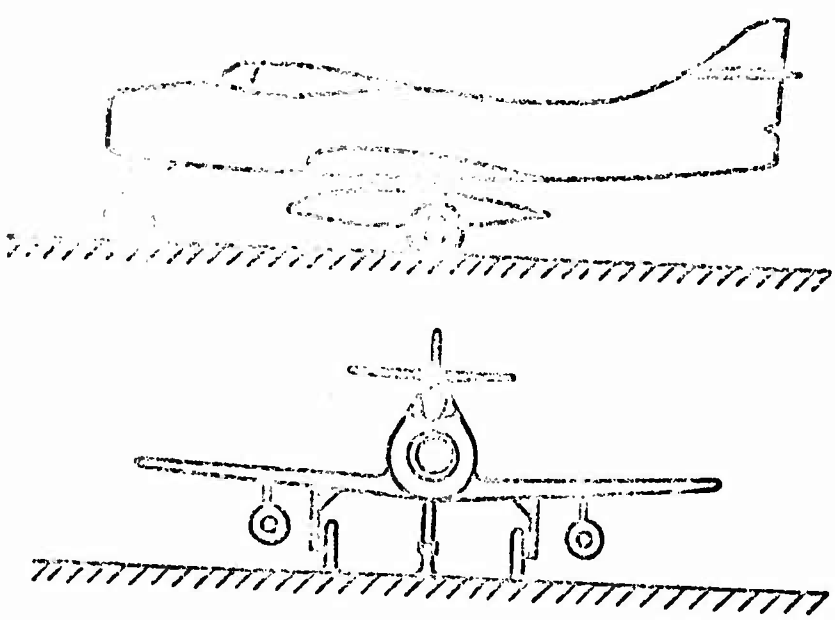


Fig.11 Example of under-wing stores making an aircraft unsuitable for undercarriage arresting

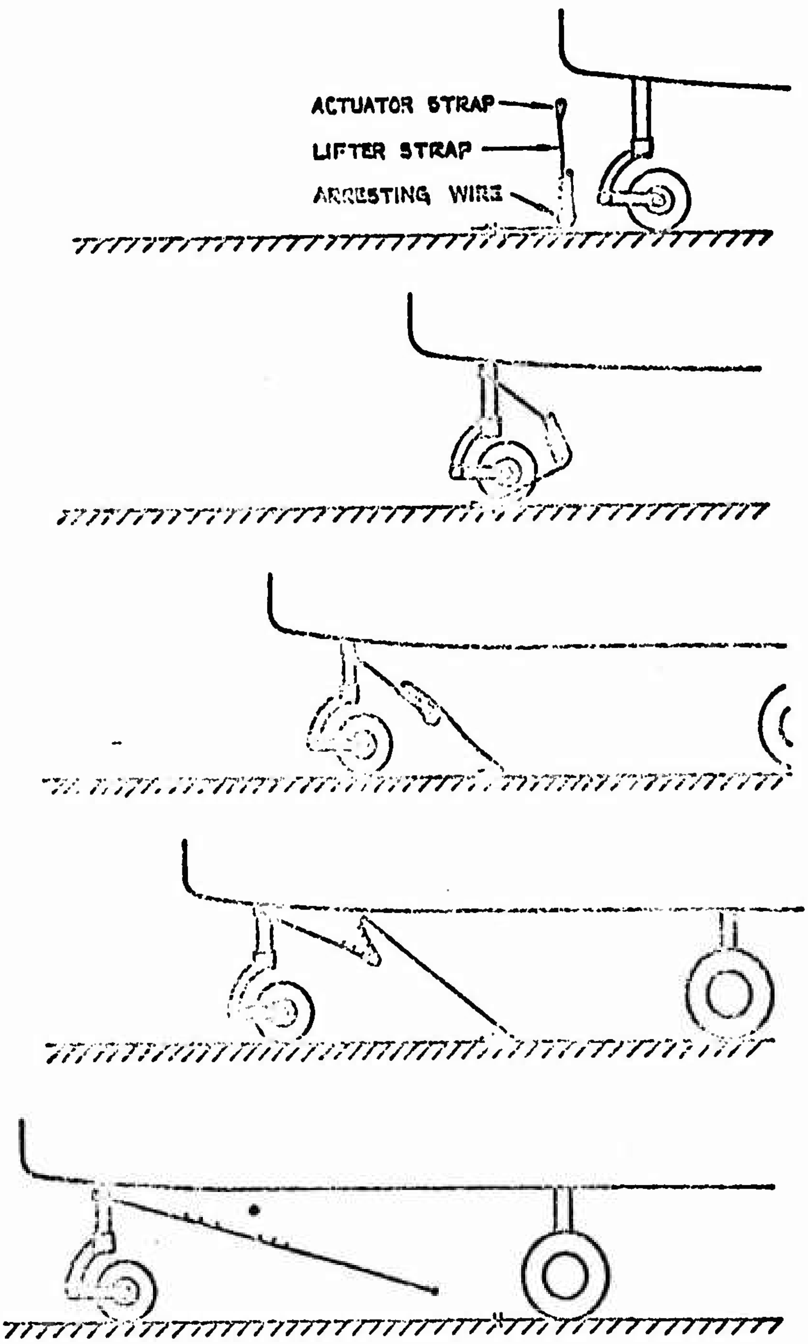
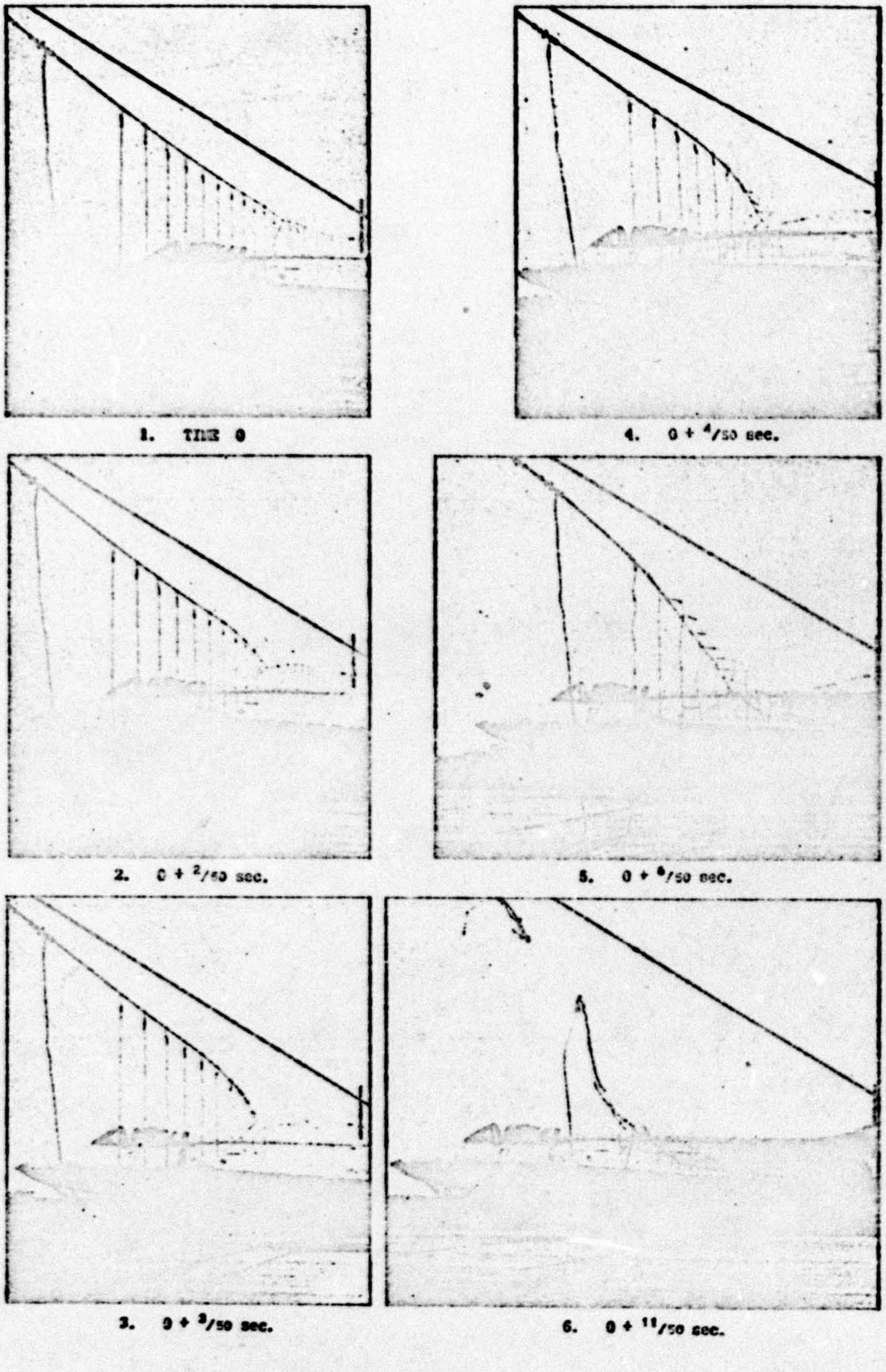


Fig.12 Operation of the 'Davis' barrier



1. TIME 0

2. 0 + $^{2}/_{50}$ sec.

3. 0 + $^{3}/_{50}$ sec.

4. 0 + $^{4}/_{50}$ sec.

5. 0 + $^{6}/_{50}$ sec.

6. 0 + $^{11}/_{50}$ sec.

Fig. 13 British airfield barrier Mk. 2

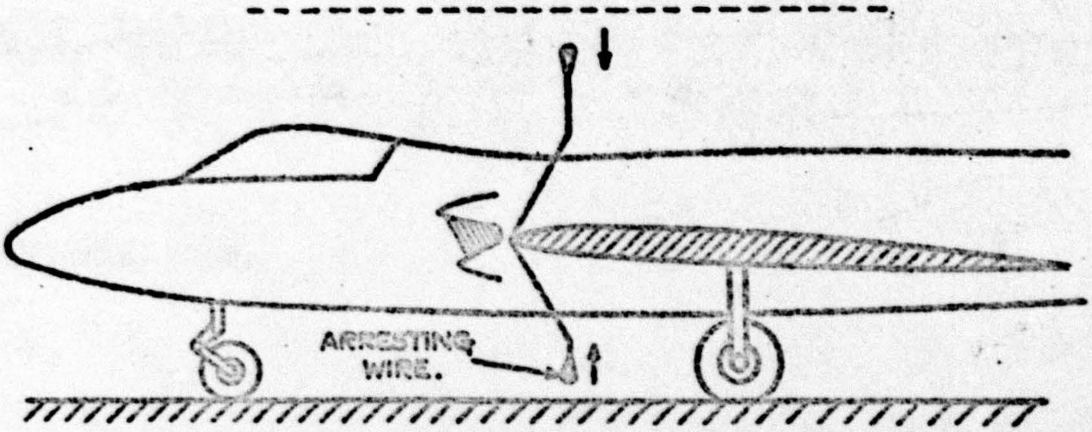


Fig.14 Arresting wire lifting action of British airfield barrier Mk.2

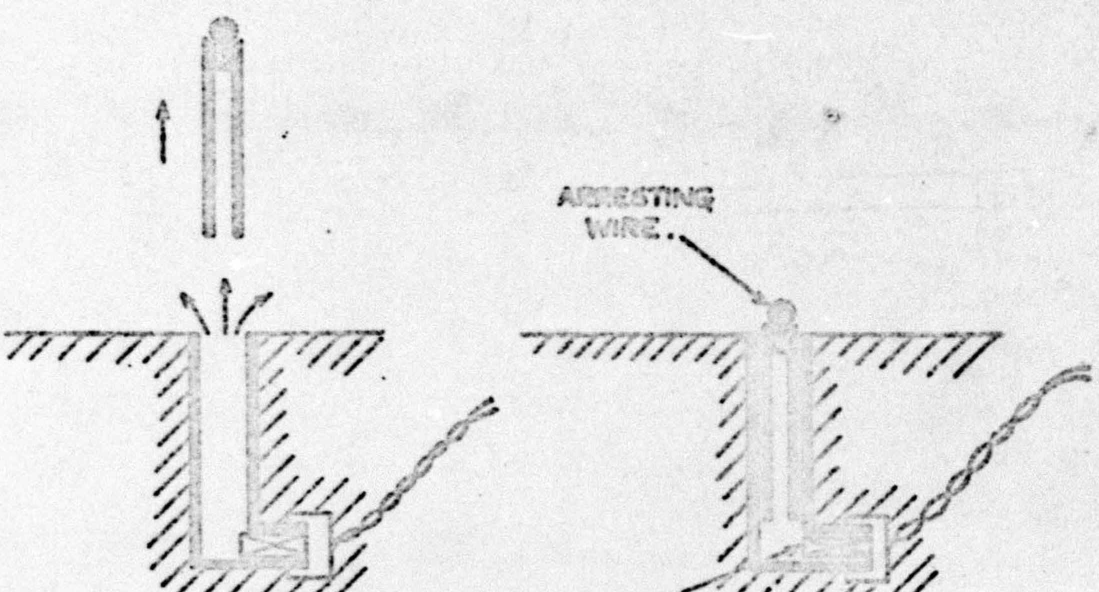


Fig.15 Pressure-operated jacks for lifting an arresting wire

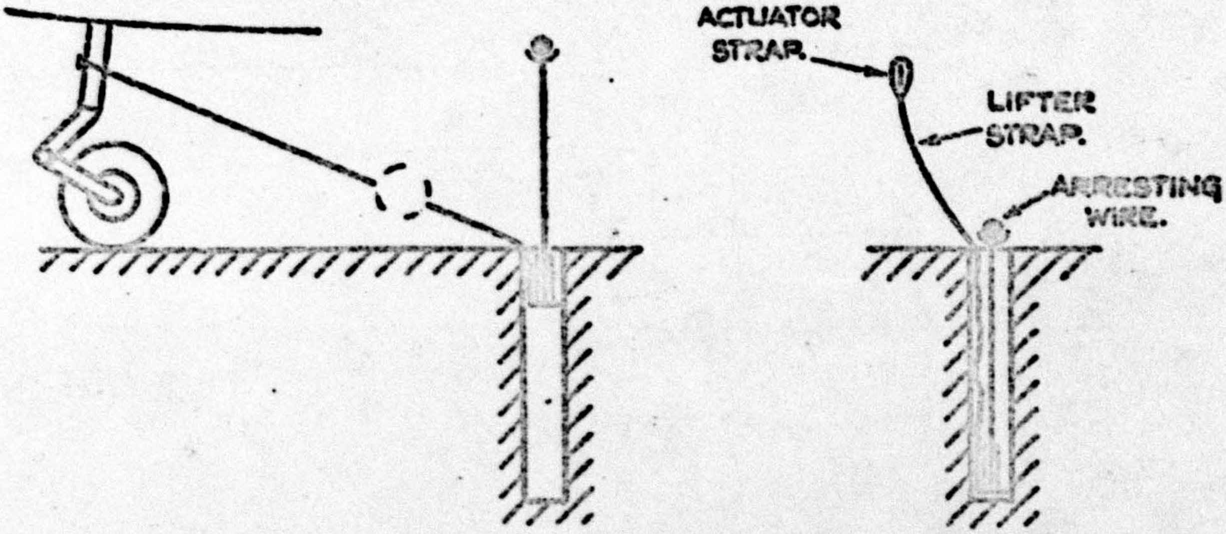


Fig.16 Aircraft-operated jacks for lifting an arresting wire

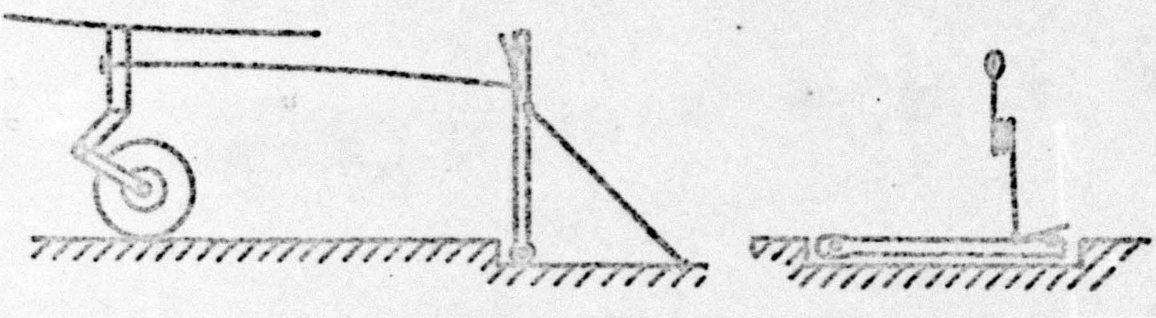


Fig. 17 Aircraft-operated levers for lifting an arresting wire

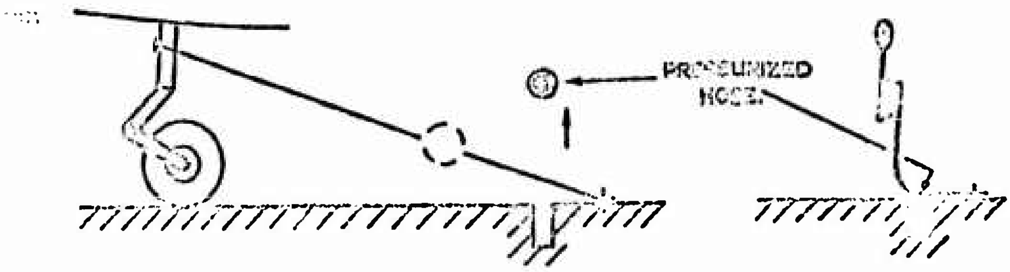


Fig.18 Pressurized hose arresting pendant

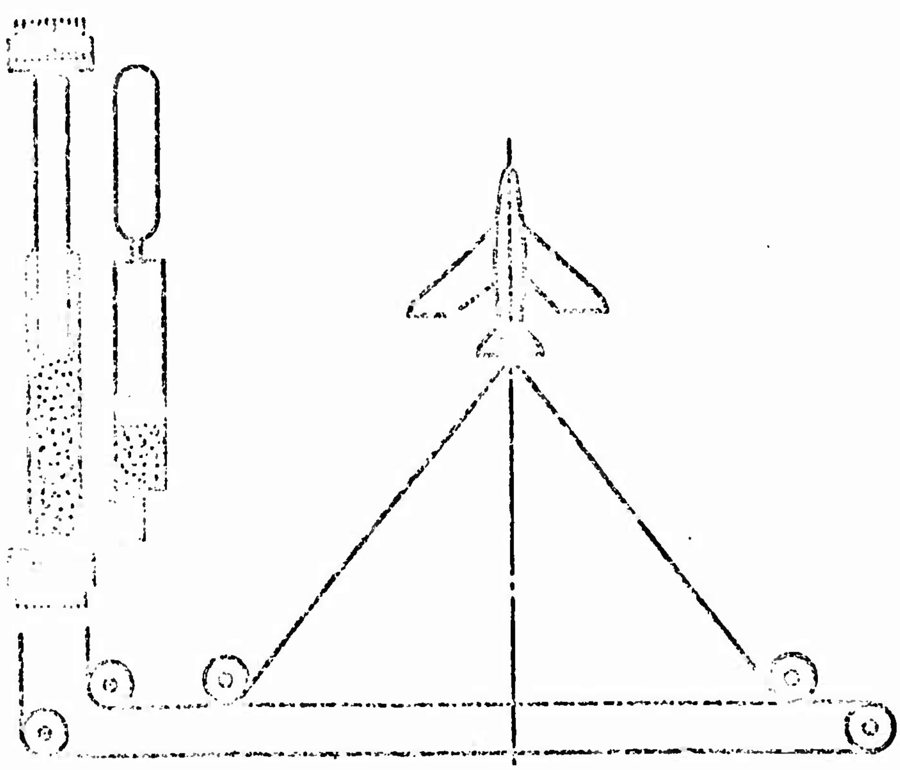


Fig.19 Hydraulic ram and cylinder energy absorber

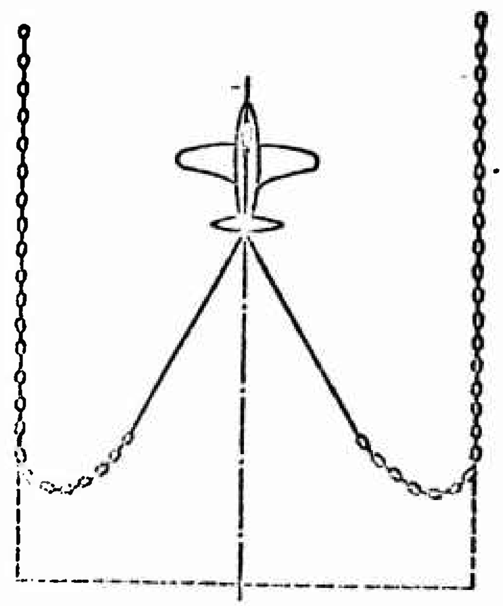


Fig.20 Drag chains. Usual arrangement

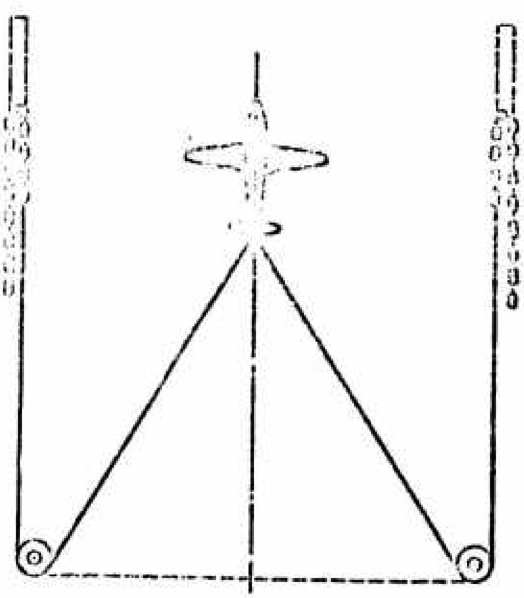


Fig.21 Drag chains with deck edge sheaves

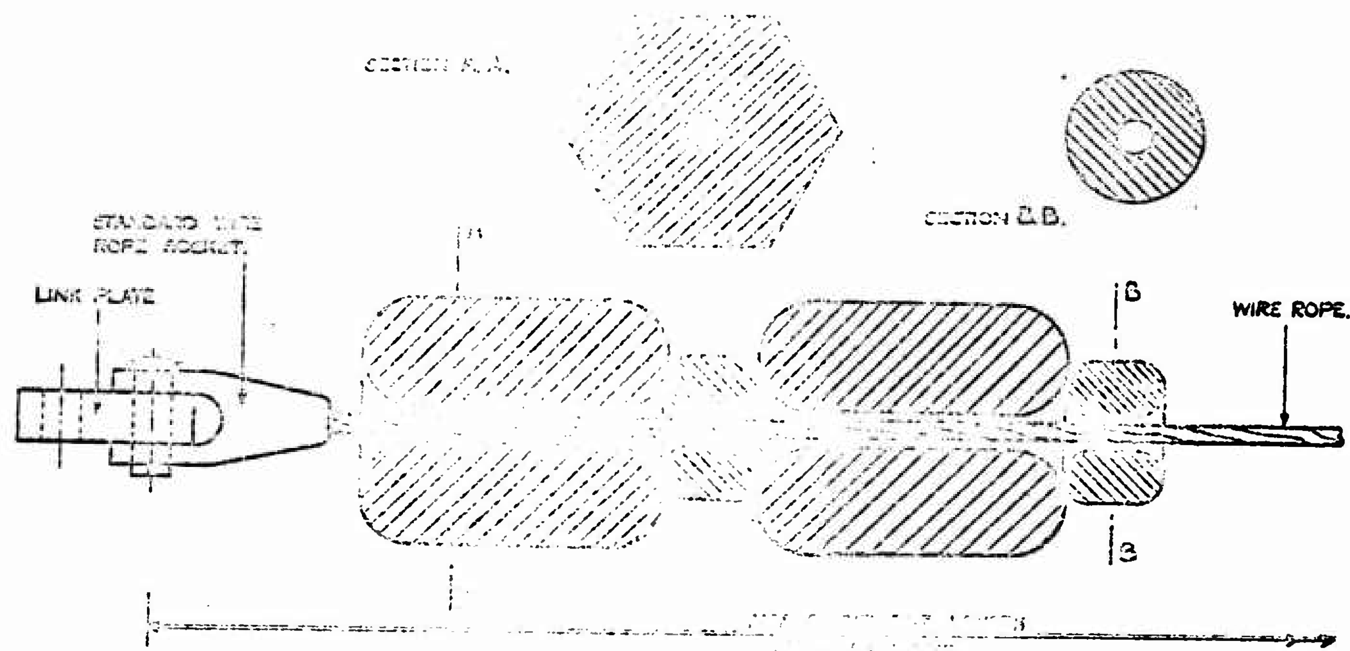


Fig.23 Cast iron bead type of drag chain

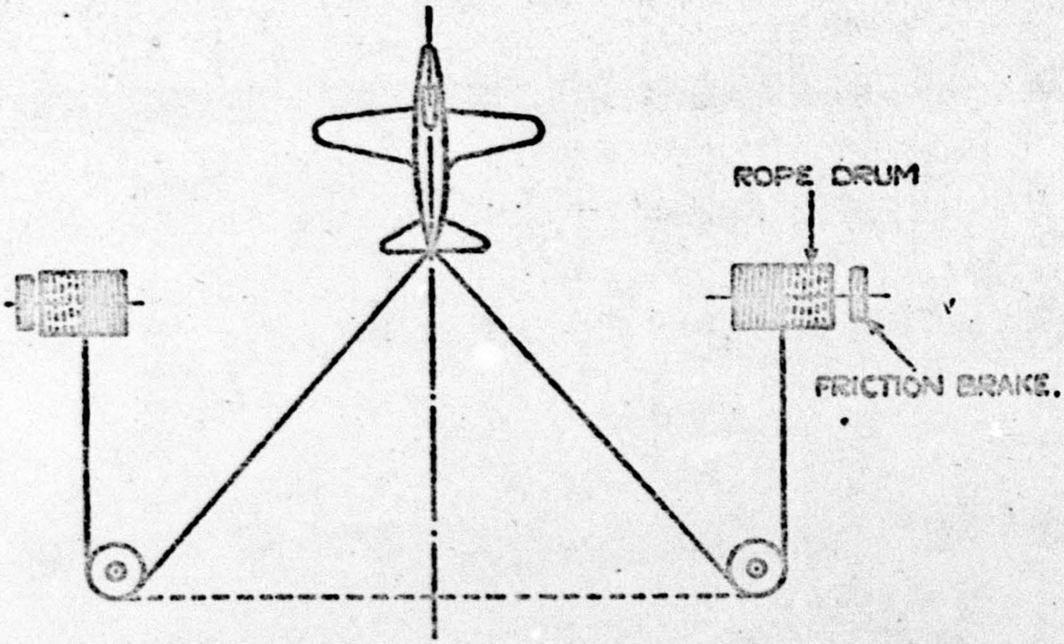


Fig.23 Rope drums with friction brakes

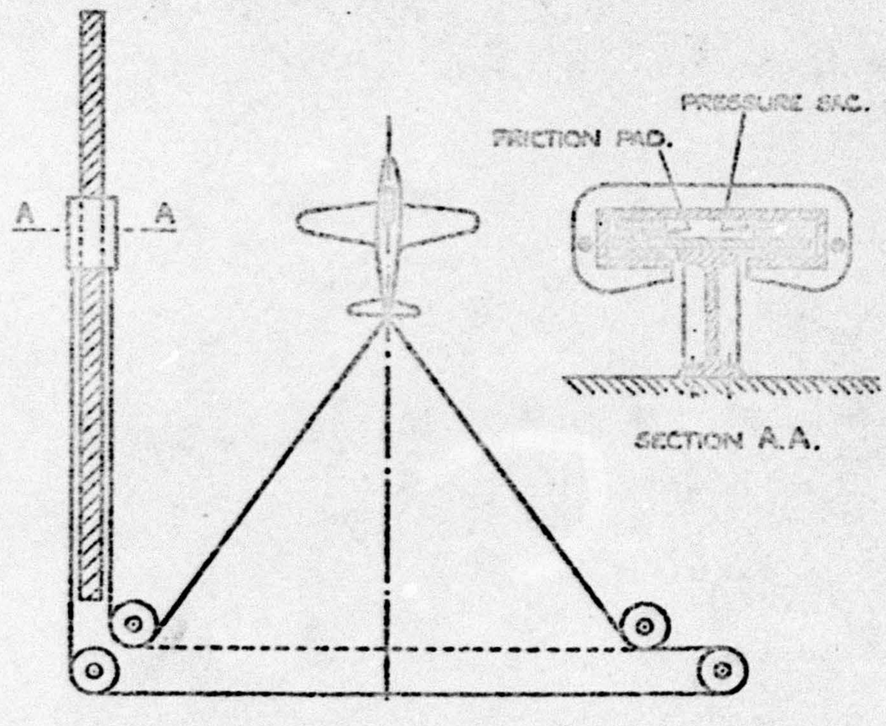


Fig.24 Friction rail scheme

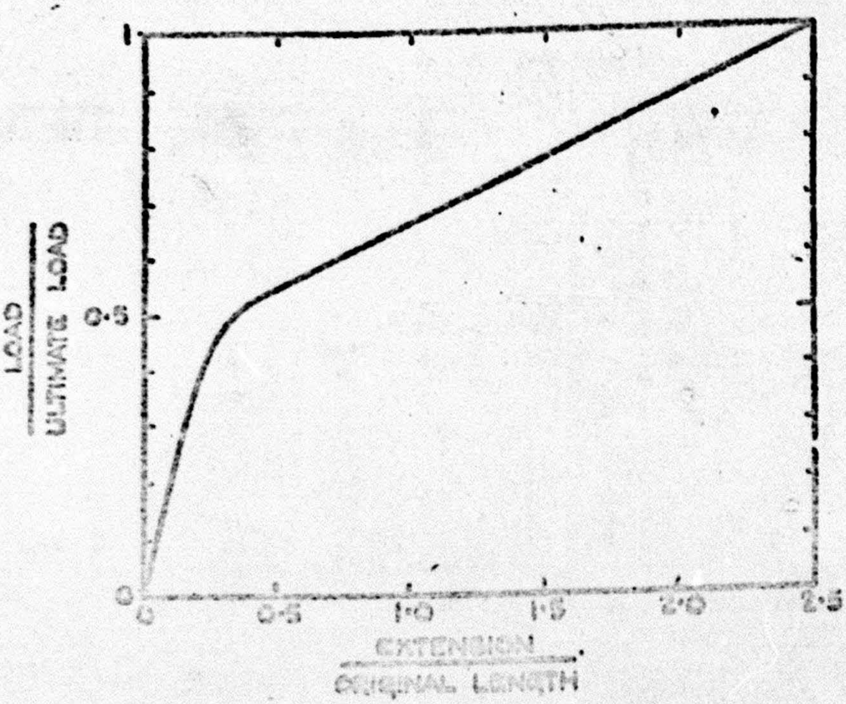


Fig.25 Approximate curve of load against extension for undrawn nylon rope

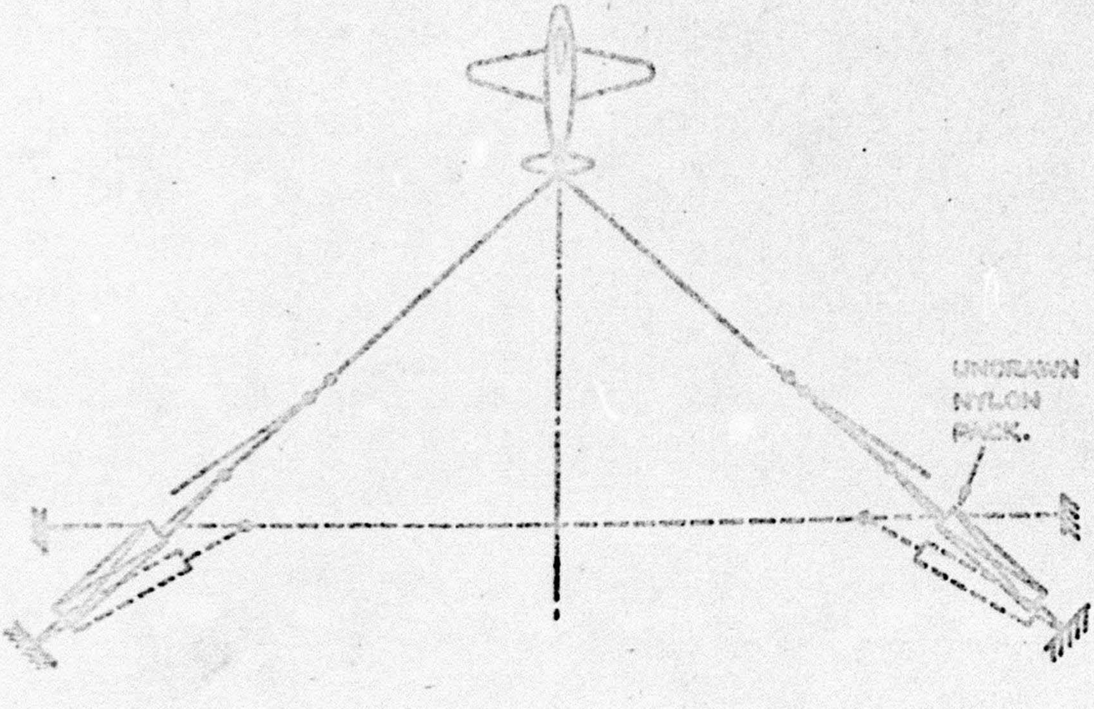


Fig.26 Layout of an undrawn nylon rope system

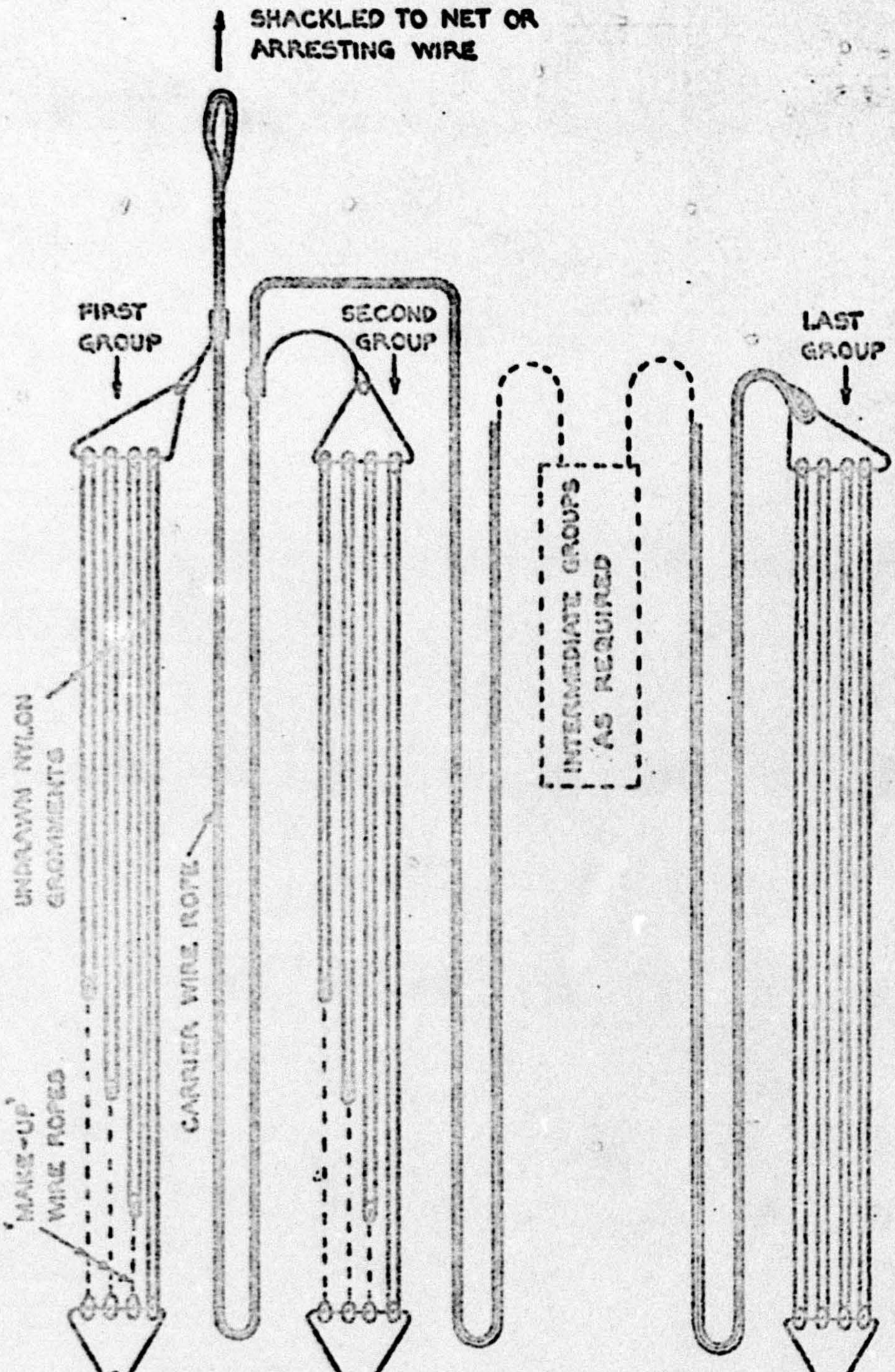


Fig.27 Diagram of undrawn nylon rope energy-absorber pack

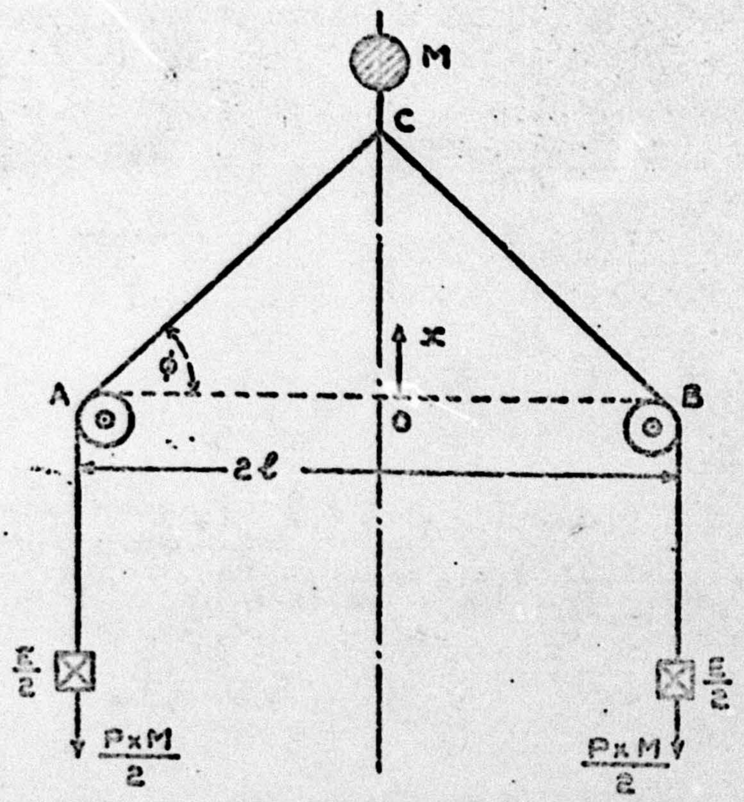


Fig.28 Simplified diagram of an arresting gear

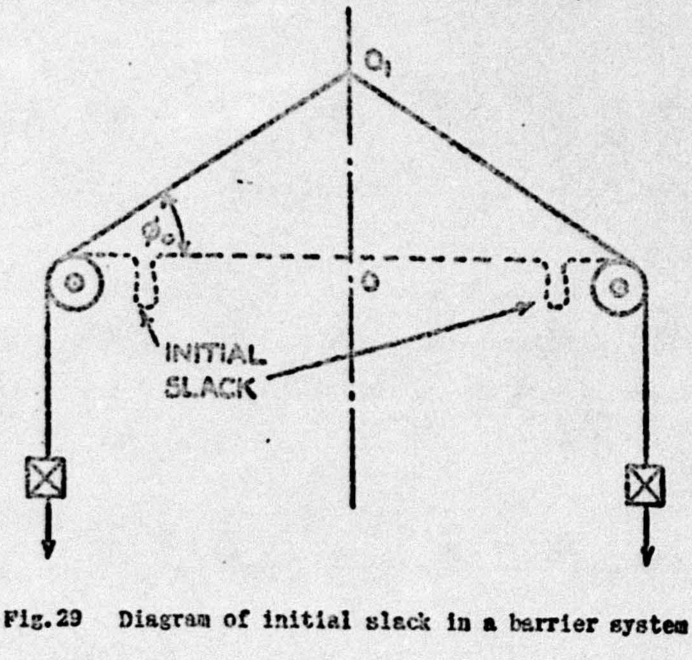


Fig.29 Diagram of initial slack in a barrier system